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ACTION OF SODIUM NITRITE IN THE SOIL[1]

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INTRODUCTION

During the past three years a substitute for Chile nitrate of soda has been manufactured and offered for sale in the Northwest as a fertilizer. Air is utilized as the source of nitrogen and apparently the Birkeland and Eyde process is followed in part. The material has been somewhat variable in composition, but recently a uniform product has been obtained containing 17.5 per cent total nitrogen, of which 14.0 per cent is in the nitrite form and 3.5 per cent in the nitrate form.

When we consider that most of the nitrogen in this product is present in the nitrite form, it is important to know its effects upon growing plants and its action in the soil. When sodium nitrite is applied to the soil as a fertilizer in quantities similar to the amounts advised for sodium nitrate, will the nitrite change as rapidly into the nitrate form as it is assumed the change takes place when nitrites are normally formed in the soil through the activity of the nitroso-bacteria? Furthermore, if the change from nitrite to nitrate is slow, what will be the effects of large quantities of nitrites upon the germinating seed and its subsequent growth?

A review of the literature does not disclose any definite information on the oxidation of nitrites that have been added to the soil. Data on the effects of nitrites on the growing plant are also somewhat inconclusive. H. G. Söderbaum (*4*)[2] in pot experiments and field tests concluded that 1 to 20 parts of nitrites per 100 parts of sodium nitrate were beneficial to oats and potatoes. O. Kellner (*2*) and A. Stutzer (*5*) both state that nitrites affect seed germination and retard early growth. The latter obtained an excellent growth of soybeans after the young plants had recovered from the early effects of nitrites. Both warned against the presence of nitrites in commercial fertilizer, except in very small amounts. L. Grandeau (*1*) reported that nitrites compared favorably with nitrates for corn and potatoes. B. Schulze (*3*) observed that calcium nitrite reduced the yields of cereals to a marked extent and concluded that nitrites are an objectionable constituent of commercial fertilizers. O. Treboux (*6*) studied the availability of various forms of nitrogen in water culture and reported that nitrites are generally available in alkaline solutions, but poisonous in acid solutions, depending upon the concentration. In a general way, it may be concluded

[1] Accepted for publication July 31, 1923.
[2] Reference is made by number (italic) to "Literature cited," p. 7.

from these investigations that for certain crops nitrites may be beneficial in small amounts, but harmful in larger quantities: also, that nitrites affect germination and retard early growth of young plants. Further investigations must be made, however, before definite conclusions can be drawn relative to the effects of nitrites on plant growth.

In view of the results obtained by previous investigators, the rapid oxidation in the soil of nitrites to nitrates seems desirable, and necessary for the best development of the plant. Accordingly, the work reported herein was undertaken in order to learn whether nitrites when used in quantities comparable to those used as a fertilizer changed rapidly to nitrates in Oregon soils.

EXPERIMENTAL PROCEDURE

The different soil types used in the experiments were prepared by passing the air-dried soil through a 10-mesh sieve with as little grinding as possible. Four hundred gm. of soil on the dry basis were then weighed out and enough distilled water added to obtain a slightly moist, crumbly condition. The soil was transferred to suitable pots and allowed to stand 24 hours. The various pots containing each soil type then received treatment as indicated in the tables. Throughout the experiment, whenever sodium nitrite was applied 0.4 gm. of the salt was added to each pot of 400 gm. of soil. Although the chemically pure salt was used, 0.4 gm. of sodium nitrite contained 0.012 gm. of nitrate calculated as NO_3. In order to facilitate thorough mixing with the soil, the sodium nitrite was first dissolved in 25 cc. of water. Finally, a fresh soil infusion was added, together with enough water to obtain optimum moisture content, as judged by the physical appearance of each type. The initial moisture content was maintained throughout the incubation period by the addition of water, except as otherwise stated, and the soils were kept at a temperature ranging between 18° and 24° C. Immediately after each pot was prepared, 10-gm. portions of the soil on a dry basis were weighed out for nitrite and nitrate determinations. Water extraction was made by shaking in a mechanical shaker for about an hour, after the addition of a small amount of aluminum hydrate for clarification of the soil solution. The bottles were then centrifuged to settle suspended particles and nitrite and nitrate nitrogen were determined in the clear solutions. Determinations were subsequently repeated at the intervals indicated in the tables.

OBSERVATIONS AND RESULTS

In choosing the soil types, attention was given more to the reaction of the soil than to its physical characteristics. Consequently, acid soils, of varying degrees of acidity as measured by the Veitch (7) method, neutral soils, and alkaline soils were selected. For convenience the soils were divided into two series. The first series as reported in Table I are acid soils, while the second series, in Table II, are neutral and alkaline soils. A brief description of the soils used in the first series is as follows:

Soil No. 11076 is classified as a clay loam having a lime requirement of 1.5 tons of calcium carbonate to the acre of 2,000,000 pounds.

Soil No. 11077 is a gravelly loam having a lime requirement of slightly less than one ton to the acre.

Soil No. 11079 is classified as a brown clay loam, and has a lime requirement of 4.5 tons of calcium carbonate to the acre.

Soil No. 11080 is a medium sandy loam, and is a type representative of a large area of coast lands. It has the very high lime requirement of 9.7 tons to the acre.

The results given in Table I show the amounts in gm. of nitrites and nitrates contained in each pot of 400 gm. of soil. The nitrites are reported as gm. of sodium nitrite, since 0.4 gm. of this salt was added to each pot, while the nitrates are calculated as NO_3.

TABLE I.—*Loss of nitrites added to acid soils*

Soil No.	Treatment.	Nitrite and nitrate after interval named.									
		Immediately.		48 hours.		6 days.		14 days.		30 days.	
		$NaNO_2$.	NO_3.	$NaNO_2$.	NO_3.	$NaNO_2$.	NO_3.	$NaNO_2$.	NO_3.	$NaNO_2$.	NO_3.
		Gm.	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*
11076	Control	None.	0.062	None.	0.062	Trace.	0.073	None.	0.079	None.	0.0[illegible]4
11076	0.4 gm. $NaNO_2$	0.310	.071	0.099	.071	Trace.	.082	Trace.	.088	....	....
11076	0.4 gm. $NaNO_2$ + 0.6 gm. $CaCO_3$	.402	.071	.263	.071	0.215	.094	0.178	.104	0.106	112
11077	Control	None.	.012	None.	.012	None.	.014	None.	.017	None.	[illegible]
11077	0.4 gm. $NaNO_2$	.381	.036	.189	.036	.015	.034	.003	.030	Trace.	29
11077	0.4 gm. $NaNO_2$ + 0.6 gm. $CaCO_3$	.395	.034	.392	.034	.280	.032	.283	.034	.160	.031
11079	Control	None.	.015	None.	.015	None.	.017	None.	.020	None.	.029
11079	0.4 gm. $NaNO_2$	.340	.035	.020	.035	Trace.	.043	None.	.036	....	....
11079	0.4 gm. $NaNO_2$ + 1.0 gm. $CaCO_3$	.400	.035	.241	.035	.238	.038	.124	.050	.006	.034
11080	Control	None.	.017	None.	.017	None.	.018	....	....	....	....
11080	0.4 gm. $NaNO_2$	.061	.027	None.	.027	None.	.027	....	....	....	....
11080	0.4 gm. $NaNO_2$ + 2.0 gm. $CaCO_3$	.320	.025	.056	.025	Trace.	.030	....	....	....	....
11080	0.4 gm. $NaNO_2$ + 1.5 gm. $Ca(OH)_2$	.326	.030	.052	.030	Trace.	.029	....	....	....	....
11080	0.4 gm. $NaNO_2$ + 0.5 gm. $CaH_4(PO_4)_2$	....	....	Trace.	.017	....	....	....	....	....	....
11080	0.4 gm. $NaNO_2$ + 4.0 gm. $CaCO_3$ + 5 gm. $CaH_4(PO_4)_2$	....	....	.285	.031	.216	.029	.116	.028	.007	.025
11080	0.4 gm. $NaNO_2$ + 3.0 gm. $Ca(OH)_2$	....	....	.362	.024	.294	.025	.203	.028	.034	.037

The data recorded in Table I present some unexpected results. In all soils that had received the sodium nitrite treatment only there was a rapid loss of nitrites until the total amount added had disappeared. Furthermore, the disappearance of nitrites was an actual loss, instead of a change from the nitrite to the nitrate form. This is plainly evident, since the increase in nitrates in the pots treated with sodium nitrite was approximately the same as in the control pots where no sodium nitrite had been added. Even treatment with calcium carbonate did not promote nitrification of the nitrites as might have been expected. Rather, the calcium carbonate functioned by retarding the loss of nitrites.

Examination of the results given at each interval for the different soils shows that the more acid the soil the more quickly are the nitrites lost. Where the soils had received calcium carbonate treatment the nitrites were retained longer. Apparently, therefore, the addition of calcium carbonate neutralized to a certain extent the acidity of the soil and thus retarded the rapid loss of nitrites. Both soils No. 11076 and 11077 lost in the course of six days practically all of the nitrite added.

However, treatment with calcium carbonate checked the loss of nitrites so that appreciable amounts were present after thirty days.

Soils No. 11079 and 11080 are strongly acid, and, consequently, the former lost most of the nitrite, and the latter all of the nitrite, in 48 hours. These soils provide conclusive evidence that the nitrites are not changed to some other form and retained, since immediately after the addition of sodium nitrite, fumes of escaping nitrous acid could easily be detected by their characteristic odor. The high acidity of these soils also furnishes equally definite evidence that the loss of nitrites is a natural consequence, owing to the reaction between the sodium nitrite and the acid soil. Considered from the standpoint of a chemical reaction the results are in accord with theoretical conclusions. When sodium nitrite is added to an acid soil it reacts with the soil minerals, causing an excess of acidity or hydrogenions in the soil solution. The reaction may be represented by the following equation:

$$NaNO_2 + HR = NaR + HNO_2$$

Subsequently the nitrous acid, which is very unstable, and exists only under abnormal conditions, rapidly escapes after decomposition, depending upon the degree of acidity formed.

In order to prove definitely whether the nitrites were actually lost from the soil by decomposition, an endeavor was made to collect the escaping nitrous acid fumes in standard potassium permanganate. An absorption tower and two bottles containing 0.1 N potassium permanganate were connected in series with a flask containing the soil. Washed air was then drawn through the apparatus. The excess potassium permanganate not reduced by the nitrous acid was then titrated with sodium thiosulphate after the addition of potassium iodid, and the amount of nitrous acid estimated. In this manner all but a small amount of the escaping nitrous acid was recovered. This result substantiates the conclusion inferred from the results given in the table that the nitrites were not oxidized to nitrates, but were lost by decomposition.

Attention is called to the effects of calcium carbonate and calcium hydroxid in retarding the decomposition of nitrites. In the case of soil No. 11080, although both calcium carbonate and calcium hydroxid had been added in sufficient amounts to neutralize the acidity of the soil, it will be observed that most of the nitrite had disappeared in 48 hours and only a trace was detected after six days. After the disappearance of nitrites these same pots were again treated with similar amounts of calcium carbonate and calcium hydroxid, or a total of 4.0 grams and 3.0 grams, respectively, for each pot. After standing 24 hours 0.4 gram of sodium nitrite was again added. To the pot receiving calcium carbonate 0.5 gram of monocalcium phosphate was also added, to observe whether the phosphate would prevent decomposition of the nitrites. Determinations made after 48 hours and after six days indicate that the acid condition had been neutralized, since the loss of nitrites was comparatively low. Monocalcium phosphate did not prevent loss of nitrites, and probably was converted into the tricalcium phosphate form in the pot where calcium carbonate was added.

In the second series particular care was taken to select soil types that were neutral and alkaline. A brief description of the soils is as follows:

Soil No. 9673 is classified as a gravelly clay loam, and is practically neutral, as indicated by the Veitch (7) method. It contains 3.4 per cent

of calcium, calculated as CaO, and is comparatively high in organic matter.

Soil No. 9675 is a gravelly loam and is likewise neutral. It contains 4.9 per cent of calcium, calculated as CaO, but is low in organic matter.

Soil No. 9615 is a clay adobe, very alkaline in reaction, and contains 10.36 per cent of free calcium carbonate.

Soils No. 9618 and No. 9619 are also classified as clay adobe soils, and contain 0.13 per cent and 3.23 per cent, respectively, of free calcium carbonate.

Soil No. 12280 is an alkali soil, containing 740 parts per million of water-soluble solids, of which 460 parts are sodium carbonate.

The soils were prepared in the same manner as in the former series, and 400 gm. of the dry soil were placed in each pot. Table II contains the amount of sodium nitrite and of nitrate as NO_3 in grams found in each pot at the time specified.

Table II.—*Decomposition of nitrites added to neutral and alkaline soils*

Soil No.	Treatment.	Nitrite and nitrate after interval named.							
		Immediately.		48 hours.		6 days.		30 days.	
		$NaNO_2$.	NO_3.	$NaNO_2$.	NO_3.	$NaNO_2$.	NO_3.	$NaNO_2$.	NO_3.
		Gm.	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*
9673	Control	None.	0.018	None.	0.018	Trace.	0.024	None.	0.037
9673	0.4 gm. $NaNO_2$	0.396	.030	0.281	.030	0.082	.038	Trace.	.066
9675	Control	None.	.009	None.	.009	None.	.012	None.	.021
9675	0.4 gm. $NaNO_2$	.400	.015	.320	.015	.240	.016	Trace.	.031
9615	Control	None.	.003	None.	.003	None.	.005	None.	.003
9615	0.4 gm. $NaNO_2$	.409	.010	.405	.010	.336	.011	0.172	.009
9618	Control	None.	.008	None.	.008	None.	.016	None.	.020
9618	0.4 gm. $NaNO_2$	.396	.014	.360	.014	.316	.021	.121	.016
9619	Control	None.	.004	None.	.004	None.	.005	None.	.006
9619	0.4 gm. $NaNO_2$	.406	.012	.394	.012	.388	.014	.176	.009
12280	Control	None.	.017	None.	.017	None.	.015	None.	.019
12280	0.4 gm. $NaNO_2$	.400	.032	.400	.032	.390	.028	.340	.030

Again, the results obtained were not in accord with expectations. There was a gradual loss of nitrites from all soils, whether neutral or alkaline. Furthermore, the decomposition of nitrites was probably similar to that occurring with the first series, and not a nitrification process, since the increase in nitrate was negligible.

It will be observed that soil No. 9673 lost its nitrites rapidly, and after six days only a small amount remained, while the decomposition of nitrites in soil No. 9675 occurred much more slowly. Although both soils were about neutral in reaction, the presence of a large amount of organic matter in soil No. 9673 probably caused the rapid decomposition of the nitrites present.

Soils Nos. 9615, 9618, and 9619, all of which normally contain various amounts of free calcium carbonate, retained the nitrites longer than the other soils discussed, but showed gradual loss. After six days' incubation no water was added to maintain the initial moisture content in these soils, and at the end of 30 days it had diminished to between 2 and 3 per cent. This treatment, which will be referred to later, contributed to the loss of nitrites.

The result obtained with soil No. 12280, an alkali soil containing an excess of free sodium carbonate, is good evidence that an acid condition,

or a hydrolytic reaction causing acidity, is the main factor contributing to the decomposition of nitrites. There was only a small loss of nitrites from this soil at the end of 30 days. In order to observe the effects of a mixture of a slightly acid soil and a soil containing free alkali, 100 gm. of soil No. 11076 was added to 200 gm. of soil No. 12280. After 14 days about one-third of the nitrite had been lost, and after 6 weeks practically all had disappeared. Thus we observe that even in the presence of an alkaline medium there is a hydrolytic reaction and attendant reactions all of which liberate the nitrites.

Particular interest attaches to observations made on the loss of nitrites in soils when the moisture content has reduced. When the acid soils were air-dried before the determinations of nitrites were made, only a trace of nitrite was found. Consequently the determinations reported in the tables were made on the moist soil. The neutral soil No. 9673 showed 0.281 gm. of nitrite when determined on the moist soil, and 0.174 gm. when determined after the sample had been air-dried. Likewise soil No. 9675 gave 0.320 gm. and 0.198 gm. of nitrite for the respective determinations. Also soils No. 9615, 9618, and 9619 lost more of the nitrite when the moisture content was allowed to diminish between the 6 days' and 30 days' period.

It is, perhaps, generally assumed that nitrites are rapidly changed to nitrates in the soil. When we consider, however, the difficulty attending the oxidation of nitrites to nitrates in the commercial preparation of nitrates from the air, it is natural to question whether nitrites do change to nitrates in the soil. The acceptance of the above results warrants the general conclusion that nitrites applied to the soil in the concentration reported do not change to the nitrate form. Furthermore, the nitrites are rapidly decomposed and lost from acid soils, and, consequently, it would seem inadvisable to apply a fertilizer containing 14.5 per cent of nitrite nitrogen to this class of soils. With neutral and alkaline soils beneficial results may be obtained, depending upon moisture and other influencing conditions. This point can not be definitely settled until more conclusive results are obtained on the assimilation of nitrite nitrogen by plants.

No reliable field observations have been made on the effects of this commercial product, although various favorable results have been reported. In these cases the crop increases may be attributed to the nitrate present. Furthermore, a possible beneficial effect may be derived from the partial sterilizing action on the soil by the decomposed nitrites. Further investigations must be made before this point can be definitely settled.

CONCLUSIONS

(1) Sodium nitrite is rapidly decomposed in acid soils, and the nitrite nitrogen lost.

(2) The nitrite nitrogen is gradually lost in neutral soils, and more slowly in alkaline soils.

(3) The oxidation of nitrites to nitrates was nil under the conditions described in these experiments.

(4) The addition of calcium carbonate and calcium hydroxid to the acid soils retarded decomposition of nitrites, but did not aid nitrification of the nitrites.

(5) It is inadvisable to apply a fertilizer composed mainly of sodium nitrite to an acid soil.

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EFFECT OF AUTOCLAVING UPON THE TOXICITY OF COTTONSEED MEAL[1]

By C. T. DOWELL, *Chemist*, and PAUL MENAUL, *Assistant Chemist, Oklahoma Agricultural Experiment Station*

Withers and Carruth[2] have found that the toxic property of the cottonseed is lessened by cooking. Osborne and Mendel[3] show that the toxicity of cottonseed meal varies with the time of steaming before the seeds are pressed.

In order to determine the effect of autoclaving upon cottonseed meal a series of feeding experiments was carried on with young pigs. A litter of four pigs, averaging 28.5 pounds each, was divided into two pens. Pen No. I was fed commercial cottonseed meal, the other, No. II, the same amount of cottonseed meal that had been autoclaved at 15 pounds for 20 minutes, in a damp condition, then dried. The daily ration for each pen was cottonseed meal one-half pound, darso 1 pound, skimmed milk 1 quart, and alfalfa. This ration was increased in proportion to the increase in the weight of the pigs. The ration was fed in such an amount that the pigs received 1.33 per cent of their body weight of cottonseed meal daily. At the end of three weeks no difference in the two lots could be noted, either in condition or in body weight, but from that time on the pigs which were fed the commercial cottonseed meal were noticeably inferior to those which were fed the autoclaved product. At the end of 73 days the average weight of the pigs in pen No. I was 52 pounds, or a gain of 23.5 pounds per pig. The pigs in pen No. II averaged 61.5 pounds per pig, showing a gain of 33 pounds per pig. The cottonseed meal was then removed from the diet, but five days afterward one of the pigs in pen No. I died and on the tenth day the other died. These pigs were examined by Dr. H. W. Orr, of the veterinary department of the Agricultural and Mechanical College of Oklahoma, who stated that death was due to the effects of the cottonseed meal. None of the pigs in pen No. II showed any ill effects from their diet.

The experiment was repeated, a different cottonseed meal being used. A control pen was established which received tankage in place of cottonseed meal in the ration. The pen receiving the commercial cottonseed meal made an average gain of 20 pounds per pig in 60 days. The pen receiving the autoclaved cottonseed meal made an average gain of 25 pounds per pig, and the control pen also made an average gain of 25 pounds for each pig. None of the animals in this experiment died, although they were continued on the several diets for 90 days.

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[1] Accepted for publication June 25, 1923.

[2] WITHERS, W. A., and CARRUTH, FRANK E. GOSSYPOL, THE TOXIC SUBSTANCE IN COTTONSEED. *In* Jour. Agr. Research, v. 12, p. 83-102, 3 fig., 1 pl. 1918. Literature cited: p. 100-101.

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Two adult sheep were used similarly; one was fed 1 pound of commercial cottonseed meal daily, the other the same quantity autoclaved. The sheep were kept on green pasture for 90 days, but since no ill effects were noted in either at the end of that time, the experiment was discontinued. This experiment was repeated, feeding two sheep, as in the previous experiment, except that the animals were kept in a dry lot and fed dry alfalfa and prairie hay as roughage. At the end of 90 days these sheep showed no ill effects.

These experiments seem to show (1) that autoclaving cottonseed meal destroys the poison peculiar to it and (2) that different lots of the meal contain different amounts of the poison. Further work will have to be done to determine whether it is the high temperature that destroys the poison or oxidation by the oxygen of the air during the drying.

THE AUXOTAXIC CURVE AS A MEANS OF CLASSIFYING SOILS AND STUDYING THEIR COLLOIDAL PROPERTIES[1]

By A. E. VINSON and C. N. CATLIN, *Division of Agricultural Chemistry, University of Arizona*

In a recent paper the writers[2] described a method of determining the swelling coefficient of dry soils when wetted. Attention was called to the existence of great differences in the rate at which swelling took place, a subject which had not been studied at that time for want of suitable equipment. Since then a MacDougal auxograph has been equipped with a rapidly moving drum, and important information on the rate of swelling is being gathered. Although the lack of time has necessarily limited the number of soils tested, the writers believe that every dry soil on swelling in distilled water at a given temperature will produce a characteristic auxotaxic curve that can be duplicated repeatedly. This curve appears to integrate at least four properties of the soil: Texture, colloidal organic matter, colloidal inorganic matter, and soluble salts, and, indirectly, specific gravity, the original thickness of the 10 gm. disk being determined by this factor. In addition to these properties of the soil itself, the curve integrates temperature, viscosity, and the presence of electrolytes and colloids in the medium in which the swelling occurs.

The accompanying auxograph charts (figs. 1 to 4) drawn by a few southwestern soils show the great variety in form of curve obtained under standard conditions. Unfortunately, the ordinate used in figures 2, 3, and 4 has twice the value of that used in figure 1. This is necessitated by the wide range in the swelling coefficient. A magnification of ten times the movement of the disk is most satisfactory, but many soils throw the pen off the chart with this magnification. Before any systematic study of the recognized soil types is undertaken, charts double the width of those shown in the accompanying figures should be provided and suitable drums constructed to carry them. It is believed that if a large number of auxotaxic curves drawn on the same coordinates and representing the recognized soil types were recorded, they could be used in the classification of soils to the greatest advantage along with other methods now in use, since the curves visualize the combined effect of many soil properties, especially those depending on colloids. It is also not unlikely that by a comparison of the auxotaxic curves of new soils with those of old ones of known behavior under cultivation the probable agricultural value of the new soil could be predicted. Such determinations might be of the greatest value in considering the desirability of installing new irrigation projects.

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[1] Accepted for publication June 25, 1923.

[2] VINSON, A. E., and CATLIN, C. N. DETERMINATION OF THE SWELLING COEFFICIENT OF DRY SOILS WHEN WETTED. *In* Jour. Amer. Soc. Agron., v. 14, p. 302-307. 1922.

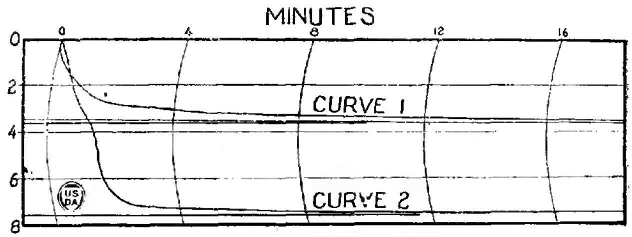

FIG. 1.—Curve 1, soil from a California orange grove, showing low swelling coefficient and auxotaxic curve with one stage. Thickness of 10-gm. disk, 5.82 mm. Curve 2, soil from the experiment station, Salt River Valley Farm, showing moderate but very rapid swelling in two stages; 10-gm. disk, 5.72 mm. Magnified 10X. Vertical scale in centimeters.

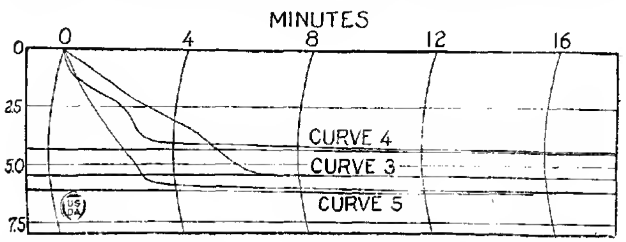

FIG. 2.—Curve 3, a silty clay recently deposited by the Rillito River near Tucson, containing a small amount of organic matter; 10-gm. disk, 5.68 mm. Curve 4, a black loam from near Tucson, showing two swelling stages of different rate; 10-gm disk, 5.63 mm. Curve 5, a calcareous clay recently deposited by the Gila River; 10-gm. disk, 5.98 mm. Magnified 5X. Vertical scale in centimeters.

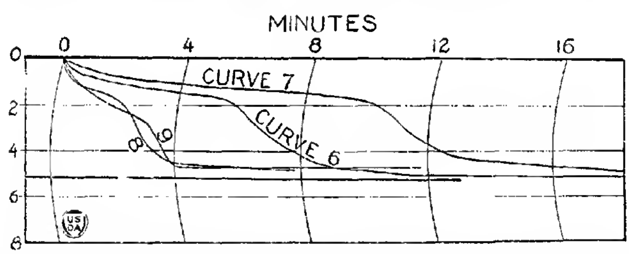

FIG. 3.—Curve 6, a calcareous clay from Utah that crushed drain tiles laterally, expanded in distilled water at 27° C.; 10-gm. disk, 5.58 mm. Curve 7, same, expanded in distilled water at 0° C.; 10-gm. disk, 5.61 mm Curve 8, same, expanded in distilled water at 70° C.; 10-gm. disk, 5.61 mm. Curve 9, same, expanded in 1 per cent sodium chlorid solution at 27° C.; 10-gm. disk, 5.63 mm. Magnified 5X. Vertical scale in centimeters.

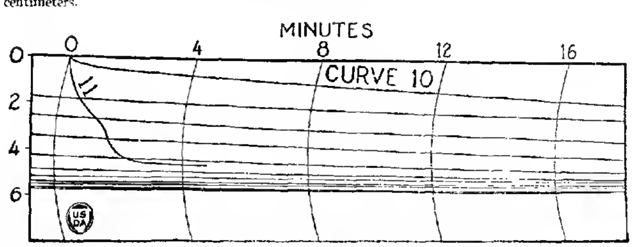

FIG. 4.—Curve 10, a calcareous, black alkaline loam very low in organic matter, from Casa Grande Valley, expanded in distilled water at 27° C.; 10-gm. disk, 5.78 mm. Curve 11, same, expanded in 1 per cent sodium chlorid solution at 27° C.; 10-gm. disk, 5.76 mm. Magnified 5X. Vertical scale in centimeters.

METHOD OF DETERMINING THE RATE OF SWELLING

In addition to the technique given in the writers' previous paper on the swelling coefficient, it is essential to determine the rate of swelling in distilled water at a constant, convenient temperature. A temperature of 27° C. has been selected as both convenient and easily maintained. Lowering the temperature retards the rate; increasing the temperature accelerates it. The curves in figure 3 show the rates of expansion of a calcareous clay at 0° C., 27° C. and 70° C. This soil from Utah, which is discussed in another connection below, is well adapted to illustrate temperature effects, since it has a rather long period of slow expansion followed by a shorter period of rapid expansion. In this case changes in temperature have the effect especially of shortening or lengthening the period of slow preliminary swelling.

While the auxotaxic curve of any soil in distilled water under standard conditions is fixed, it may be modified by the addition of electrolytes, molecules such as sugar, or colloids. Electrolytes in the water accelerate the rate of swelling and cause the curve to approach in form that obtained in distilled water at 70° C. Figure 3 illustrates the action of 1 per cent sodium chlorid in accelerating the rate of swelling of the calcareous clay from Utah. Figure 4 shows how 1 per cent of sodium chlorid caused a slowly expanding soil to swell as much in a few moments as it had in more than an hour in distilled water. The curve representing the rapid swelling, moreover, takes on the two-period form so noticeable in most of the other curves. Unmistakable acceleration is produced by 0.05 per cent sodium chlorid. Twenty per cent of cane sugar retarded the swelling of this clay, giving a curve almost identical with that of water at 0° C. (curve not reproduced here). Small amounts of gelatin accelerate the rate of swelling and large amounts retard it. It is possible that the retardation of the swelling by strong sugar or colloidal solutions may be due to increased viscosity. This subject is being studied. The fact that the same concentration of colloid has a markedly different effect on the rate of expansion of different soils suggests that here also may be found another means of studying the colloidal properties of different soils. Small amounts of electrolytes accompanying strong solutions of gelatin also greatly modify its effect.

LATERAL CRUSHING OF TILE EXPLAINED BY THE AUXOTAXIC CURVE

The calcareous clay from Utah mentioned above was submitted to the writers by R. A. Hart, senior drainage engineer of the Bureau of Public Roads, Salt Lake City, with the statement that tiles laid through it were always broken by lateral pressure. With the aid of the auxotaxic curve (fig. 3) the cause of the failure of the pipe line seems evident. The soil on the ditch bank dries out to a considerable degree and when the back fill is made the slow preliminary swelling serves to compact the soil firmly in the ditch and about the pipe. The second period of more rapid swelling, acting against the ditch wall and confined by the firmly packed soil above would serve to crush the tile laterally. The coefficient of expansion of this soil, moreover, is 187.5, which is among the highest coefficients obtained for any soils which the writers have so far examined.

SOME OBSERVATIONS ON THE TEMPERATURE OF THE LEAVES OF CROP PLANTS[1]

By Edwin C. Miller,[2] *Plant Physiologist, Department of Botany, Kansas Agricultural Experiment Station*, and A. R. Saunders, *Senior Student, Kansas State Agricultural College*

INTRODUCTION

In investigating the water relations of various crop plants at the Kansas Agricultural Experiment Station it was thought advisable to study the temperature of leaves of these plants under natural field conditions. Especially it seemed desirable to consider the temperature-relationships of leaves under conditions of a limited water supply, since a lack of moisture is the limiting factor in crop production in the Great Plains area and in regions adjoining it. It is commonly stated that transpiration under conditions that furnish a sufficient supply of water to the roots of plants prevents the temperature of the leaves from becoming so high as to interfere with their normal life activities, but experimental evidence on this point is rather limited and fragmentary. In order to obtain some information on this question, investigations were undertaken to study the temperature of leaves along the following lines:

(1) The relation of leaf temperature to the rate of transpiration.

(2) Leaf temperatures during the day and night.

(3) Temperature of different portions of the leaf under like conditions.

(4) The temperature of leaves in direct and in diffuse light.

The data reported in this paper were obtained at Manhattan, Kans., during the growing season of 1922. The literature in regard to the temperature of leaves has been thoroughly reviewed by Ehlers (*5*)[3] and will be mentioned here only in the discussion of the various phases of these experiments.

METHODS OF EXPERIMENTATION

DESCRIPTION OF APPARATUS

In these experiments the temperature of the leaves was measured by a modification of the method reported by Shreve (*11, p. 12, 13, 50-57*), a diagram of the apparatus used being shown in figure 1. It consisted of two thermojunctions TC and T'C', approximately 5 mm. in length, which were formed by braiding the two wires and then uniting them by an acid-free solder. The wires used were No. 36 copper and No. 36 constantan, with insulated connecting length A, B, and B', totaling approximately 3 feet.

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[2] Acknowledgments are due Prof. E. V. Floyd and G. E. Raburn, of the department of physics, Kansas State Agricultural College, for their aid and advice in regard to the temperature measurements.

[3] Reference is made by number (italic) to "Literature cited," p. 43-44.

One of the thermojunctions was placed with a thermometer graduated to 0.1° C. in a stoppered Dewar flask, DF, containing a small amount of water, W, and surrounded by a jacket of glass wool and water, GW, in a

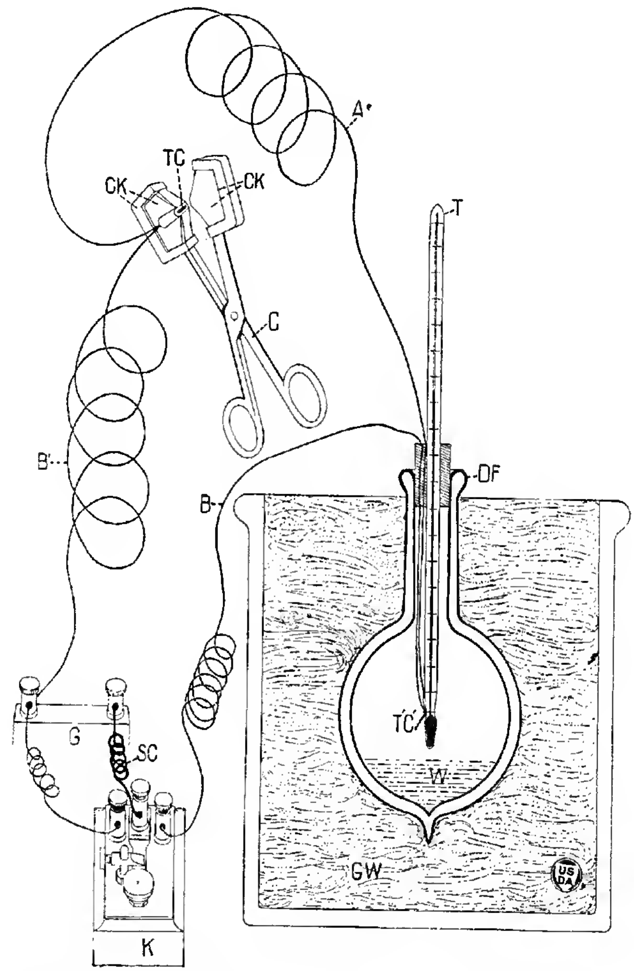

FIG. 1.—Diagram of the apparatus used in determining the surface temperature of leaves: TC, T'C', thermojunctions; A, insulated constantan wire No. 36; B, B', insulated copper wire No. 36; C, clamp for holding thermojunction on leaf; CK, cork insulation; G, galvanometer; K, key; SC, short circuit; DF, Dewar flask; W, water in flask; GW, glass wool and water surrounding the flask; T, thermometer.

2-gallon porcelain jar. The temperature of the air in the flask remained practically constant, since under the most severe conditions it did not fluctuate more than 0.1° C. during a 15 to 20 minute period.

The other thermojunction, TC, was attached to a clamp, C, in such a way that it could be conveniently placed upon the surface of a leaf. This clamp consisted of a pair of brass tongs modified by completely inclosing their distal ends with heavy layers of cork, CK, shaped into a wedge form so that the dimensions of the edges in contact when the clamp was closed were only 3 by 10 mm. By means of a clamp of this kind the thermojunction could easily be placed as desired in direct contact either with the upper or lower surface of the leaf, and the temperature thus determined. Similarly, the temperature of the air could readily be determined by holding the open clamp in the air and taking precautions to shield the thermojunction from the direct rays of the sun by the cork of the clamp.

A portable telescopic galvanometer, G, with a sensitivity of 0.025 microamp. and with a scale having divisions of one-half cm., graduated to tenths, was placed in the circuit, which, with a damping switch, S, completed the main part of the apparatus. In addition, a thermometer, T, graduated to 0.1° C. was used for taking the temperature of the air for comparison with the temperatures obtained by means of the galvanometer. Since the temperature of the thermojunction, T'C', was known and could be kept approximately constant, the difference in temperature between T'C' and TC could be calculated from the swing of the galvanometer. It was found that for a considerable range of temperature a deflection of one scale division indicated a difference in temperature of 1° C. between the two thermojunctions, and that under the conditions of the field a difference of 0.1° C. could be accurately detected.

The apparatus when in use in the field was placed upon a small, specially constructed table, shaded by a heavy piece of canvas placed about 2 feet above its surface. When vines and other low plants were the subject of investigation, the apparatus was placed on a low box and shaded with an umbrella. The clamp and its thermojunction, as well as a portion of the connecting wires, were not shaded, but were always freely exposed to the atmospheric conditions prevailing during the experiments. As the temperature determinations were largely comparative ones, the errors that might be due to the absorptions of heat by the clamp and exposed portions of the wires were not taken into consideration.

LEAF TEMPERATURE DETERMINATIONS

The temperature determinations herein reported were made upon the attached leaves of plants growing either in the field or in large metal containers that were exposed to field conditions. Certain leaves upon the same plant or upon different plants were selected for a given series of temperature determinations, care always being taken to select leaves of about the same age and with approximately the same exposure to the incident rays of the sun. After the leaves for an experiment had been selected, the table containing the apparatus was brought into a position where the thermojunction could be conveniently placed upon the leaves to be studied. The surface of the table was always brought to a level position before any determinations were made, for, unless this is done, the galvanometer readings of one set of experiments are not comparable to those of another. All the temperature determinations were made by two persons. One by means of the clamp held the thermojunction on the leaf while the other pressed the key and recorded the swing of the galvanometer. In this manner the swing of the galvanometer in any given determination could be read in approximately two to three seconds.

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The time, however, that elapsed during the recording of the deflection and the return of the galvanometer to equilibrium amounted to approximately 10 to 12 seconds, so that an interval of about 15 seconds occurred between any two consecutive temperature observations.

Since it was observed that the temperatures of the leaves and the surrounding air were subject to rapid and marked fluctuations, it was considered that the average of several determinations would more nearly represent the general temperature relations of the leaves and the surrounding air than would a single observation. On that account, each temperature value reported in the following tables is the average of from 10 to 20 different determinations usually taken during a 15 to 20 minute period. The manner in which the temperature values reported in the tables were obtained can best be illustrated by the following example: If Table IV, part 3, is examined, it is observed that the temperatures recorded on July 18, 1922, from 11.15 to 11.30 a. m. for the air, corn leaves, and milo leaves are 29.3°, 29.9°, and 29.6° C., respectively. Each of these temperatures is the average of the 20 consecutive determinations of the temperatures of the air, corn leaf, and milo leaf, shown in Table I.

TABLE I.—*Deflections on the galvanometer scale in 20 temperature determinations of the air and of the leaves of corn and milo from 11.15 to 11.30 a. m., July 18, 1922*

Air.	Corn.	Milo.	Air.	Corn.	Milo.
7.5	6.5	7.0	6.1	6.4	5.4
6.5	7.0	7.5	5.5	5.7	5.7
7.0	7.5	7.2	5.0	5.5	5.8
6.8	7.2	7.2	6.1	6.7	5.8
5.1	6.1	6.8	6.3	8.1	7.2
6.0	6.4	6.5	6.3	7.0	6.0
6.0	6.0	5.8	6.4	8.0	6.6
5.7	6.5	7.0	6.5	7.5	6.5
6.4	5.8	5.1	5.5	7.3	6.6
5.2	4.6	4.8	6.8	8.1	7.0
Average deflection on the scale			6.1	6.7	6.4
Temperature of constant			23.2	23.2	23.2
Temperature (° C.)			29.3°	29.9°	29.6°

During this experiment the air was clear, a slight breeze was blowing, and the reading of the constant temperature junction was 23.2° C. Since the deflections were to the right on the galvanometer scale, and since a deflection of one scale division indicates a difference in temperatures of 1° C. between the two thermojunctions, the temperature of the air and of the leaves in question was obtained by adding each of the average deflections to the constant temperature 23.2° C.

DETERMINATION OF TRANSPIRATION

The transpiration experiments were performed upon normal plants which were grown in large metal containers after the manner previously reported by Miller and Coffman (9). The soil used in the containers was a sandy loam in good tilth, and had a moisture content of 23.3 per cent and a wilting coefficient of about 12 per cent. In order to determine

the relation between the rate of transpiration and the temperature of the leaves, experiments were conducted with both turgid and wilted plants. The plants designated as turgid were those which showed no visible signs of wilting during the transpiration experiments. The soil in the containers in which these plants were growing was kept at a moisture content of approximately 23 per cent by the frequent addition of water to replace that which was lost from the plants. In order to obtain wilted plants, certain containers were set aside to which no water was added to replace that lost by transpiration. The plants were considered sufficiently wilted for the experiments when they did not regain their turgid condition during the night. The water content of the soil in which the wilted plants were rooted averaged during the transpiration experiments about 2 per cent above the wilting coefficient. The loss of water from the plants was determined every two hours by weighing the containers on platform scales sensitive to 7 gm. After each experiment the leaves were removed from the plants and their outlines traced on unruled paper. The areas inclosed by these outlines were later measured by a polar planimeter, and from the data thus obtained the rate of transpiration per unit of leaf surface was calculated. The evaporating power of the air during the experiments was measured by means of Livingston spherical porous cup atmometers.

EXPERIMENTAL DATA

The temperature of an intact leaf of a plant exposed to natural field conditions is influenced by numerous factors, the most important of which are the temperature of the air, the supply of available moisture in the soil, air currents, the evaporating power of the air, and the intensity of the light to which the leaf is exposed. Under identical conditions the temperature of one kind of leaf is different from that of another kind, while different regions of the same leaf have different temperatures. Owing therefore to the numerous factors influencing the temperature of leaves, any data presented upon that subject must be regarded as relative only to the conditions that prevailed when the temperature determinations were made.

FLUCTUATIONS IN TEMPERATURE

In direct sunlight when the temperature is relatively high and when the air is in motion, the temperature of the leaves of plants and the surrounding air is not constant, but shows sudden and marked fluctuations, even during so brief a period as a few seconds. These changes in temperature, which vary from a small fraction of a degree centigrade to as high as 4° C. or more, are easily detected by the galvanometer, but are of such short duration that as a rule they are not visibly recorded by a mercury bulb thermometer, even when it is graduated to tenths of a degree. These rapid fluctuations in the temperature of the air are due in all probability to the fact that the air is not uniformly heated throughout, but contains warmer or cooler pockets which suddenly replace the air surrounding the measuring instruments. The leaves of plants respond very quickly to the changes in temperature of the surrounding air, for even a very slight increase or decrease in the temperature of the air is almost immediately followed by a corresponding change in the temperature of the leaves. When the air is still and when the temperature is relatively low, the fluctuations in the temperature are so few and so small

that they are seldom detected even by the galvanometer. Some data in regard to the fluctuation of the temperatures of the air and of leaves are shown in Tables II and III, and are illustrated by graphs in figures 2 and 3.

TABLE II.—*Fluctuations in the temperature of the air and of the leaves of wilted and turgid cowpeas from 1.15 to 1.30 p. m. on July 28, 1922, as recorded by twenty observations*[1]

Air.	Wilted leaves.	Turgid leaves.	Air.	Wilted leaves.	Turgid leaves.
°C.	°C.	°C.	°C.	°C.	°C.
36.0	41.3	35.1	35.5	42.5	35.4
35.9	43.0	35.0	35.8	42.3	35.2
35.5	41.5	34.5	35.2	40.0	35.0
37.0	45.0	37.5	35.4	40.0	34.6
37.0	46.0	36.5	35.7	40.8	35.2
36.7	43.5	36.4	35.2	40.1	35.0
34.7	41.5	35.8	35.5	40.5	35.3
35.0	41.2	35.0	36.0	42.0	35.6
35.3	42.0	33.6	37.0	42.0	36.5
35.0	41.3	35.0	37.5	43.0	36.7

[1] The sky was clear and a brisk breeze was blowing.

TABLE III.—*Showing the slight fluctuations of the temperature of the air and of the leaves of plants during periods when the air is still*

JULY 26, 8.20 to 8.30 p. m.			JULY 26, 10.30 to 10.40 p.m.		
Air.	Cowpea leaves.	Pumpkin leaves.	Air.	Water-melon leaves.	Sudan grass leaves.
°C.	°C.	°C.	°C.	°C.	°C.
22.9	22.9	22.7	22.2	22.3	22.2
22.9	22.8	22.7	22.2	22.0	22.1
22.9	22.8	22.6	22.1	22.0	22.0
22.8	22.6	22.5	22.1	22.0	22.1
22.9	22.6	22.5	22.2	22.2	22.2
22.7	22.4	22.4	22.3	22.2	22.2
22.7	22.4	22.4	22.1	22.1	22.1
22.6	22.3	22.3	22.2	22.2	22.1
22.6	22.3	22.3	22.0	22.0	22.0
22.6	22.3	22.3	22.1	22.0	22.1
JULY 26, 10.10 to 10.20 p. m.			**JULY 27, 12.20 to 12.30 a. m.**		
21.8	22.0	21.5	23.1	23.1	23.3
21.8	21.6	21.5	23.1	23.1	23.4
21.8	21.8	21.6	23.2	23.2	23.1
21.8	21.8	21.6	23.1	23.1	23.4
21.7	21.8	21.6	23.1	23.0	23.1
21.8	21.8	21.5	23.1	23.1	23.1
21.6	21.7	21.5	23.2	23.1	23.1
21.7	21.8	21.5	23.1	23.1	23.1
21.6	21.6	21.5	23.1	23.1	23.1
21.6	21.6	21.4	23.1	23.1	23.1

RELATION OF LEAF TEMPERATURE TO THE RATE OF TRANSPIRATION

It is commonly stated that the temperature of a wilted leaf exposed to the direct rays of the sun is higher than that of a turgid leaf exposed to the same conditions, but very little quantitative work has been done on the subject.

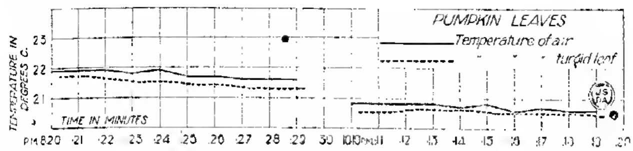


FIG. 2.—Graphs showing that there is only slight fluctuation in the temperature of the air and of turgid leaves during any given period when there is little or no breeze and when the temperature of the air is relatively low. Pumpkin leaves, 8.20 to 8.30 p. m. and 10.10 to 10.20 p. m., July 26, 1922.

Darwin (*4*) in the observation of withered detached leaves and normal attached leaves of *Tropaeolum majus* found in intermittent sunshine and relatively low humidity that the temperature of the withered leaves was from 1.2° to 3.9° C. higher than that of the attached leaf. Smith

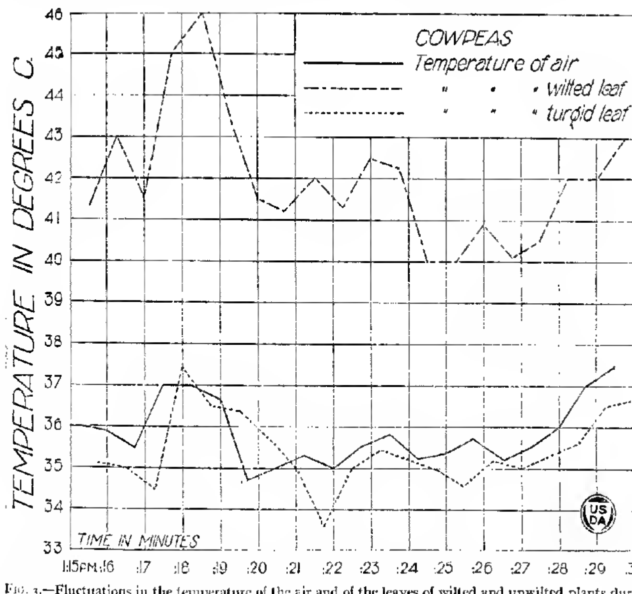


FIG. 3.—Fluctuations in the temperature of the air and of the leaves of wilted and unwilted plants during a 15-minute period when the temperature was relatively high and when a brisk breeze was blowing. July 28, 1922.

(*14*) observed that when two leaves of *Amherstia mobilis* were so placed that the surfaces containing the stomata were in direct contact, the temperature of the leaves was 2.5° C. above that of the same leaves when the surfaces bearing the stomata were placed facing outward.

Kiesselbach (*6, p. 115–117*) in his study of the water relations of corn reported some preliminary experiments with the temperature of the turgid and wilted leaves of that plant. By inserting the bulb of a thermometer momentarily in the fold of the leaves he found that a transpiring leaf of corn was uniformly cooler than a dry dead one, the difference in temperature amounting in one case to as much as 8.5° F. in direct sunshine at 2 p. m., and to 4.2° F. in the shade. The average daily temperature of the green leaf was found to be 2.2° F. below the air tempera-

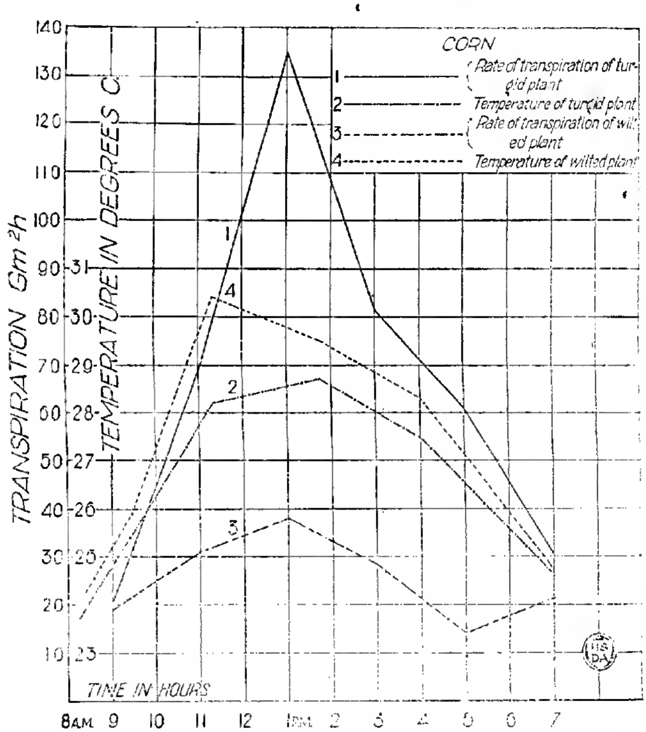


FIG. 4.—Transpiration rate of turgid and wilted corn plants and temperature of the leaves of these plants at different periods of the day, August 4, 1922.

ture, while the dry leaf was 1.6° F. higher than the air. Using a similar method, Loftfield (7) made a few observations on the temperature of the leaves of alfalfa, potato, and sugar beet in relation to stomatal behavior. He found that usually the temperature of the leaves with the stomata open was lower than that of the air and that the temperature of the leaves with closed stomata was higher than that of the air.

The transpiration-temperature experiments herein reported were conducted with turgid and wilted plants of Pride of Saline, Freed White Dent and Kansas Sunflower varities of corn; feterita, Dwarf Yellow milo and Freed sorgo of the sorghums; New Era cowpeas; and Medium Yellow

soybeans. These experiments ranged in duration from 8 to 24 hours, and with but one exception, extended only through the daylight hours. The rate of transpiration was determined at intervals of two hours, and the temperature determinations were made at times intermediate between these periods. The detailed data obtained in the experiments are reported in Table IV. The graphs shown in figure 4 illustrate the response of the turgid and wilted leaves of corn to the climatic conditions of August 4, 1922.[4] Such a response is typical of the general behavior of the turgid and wilted leaves of plants in regard to temperature and the rate of transpiration.

[4] The symbol "gm²h," used in Table IV and figure 4, means grams per square meter of leaf surface per hour, and is commonly used by plant physiologists to express the rate of transpiration or photosynthesis.

TABLE IV.—*Comparison of the temperature of the leaves and the hourly rate of transpiration of plants under optimum and limited water supply*

PART 1

Temperature of the air and the upper surface of the leaves (°C.).[1]

Time.	Evaporation.	Temperature of air.	Corn (Pride of Saline).	
			Turgid.	Wilted.
JULY 8.	*Cc.*			
10 to 10.25 a. m.	....	28.2	28.3	29.2
11.15 to 11.35 a. m.	....	29.9	30.2	32.5
1.15 to 1.40 p. m.	....	32.9	33.5	36.0
JULY 14.				
9.15 to 9.45 a. m.	0.5	29.3	29.8	32.3
11.10 to 11.30 a. m.	.7	30.7	30.2	32.4
1.15 to 1.30 p. m.	.6	31.8	32.3	34.7
3.30 to 3.50 p. m.	....	33.1	33.1	36.4

Time.	Evaporation.	Temperature of air.	Feterita.	
			Turgid.	Wilted.
JULY 8.	*Cc.*			
10.30 to 10.50 a. m.	....	29.0	29.1	29.7
11.40 to 12 m.	....	30.5	30.8	31.1
1.45 to 2.10 p. m.	....	33.0	33.1	34.1
JULY 14.				
9.45 to 10 a. m.	0.6	29.2	29.2	30.5
10.20 to 10.40 a. m.	.6	30.6	30.5	31.5
11.35 to 12 m.	.6	32.5	32.1	33.1
1.35 to 1.55 p. m.	.6	33.6	33.3	35.4
4 to 4.15 p. m.	....	32.4	32.6	33.0

Rate of transpiration (gm²h).

Time.	Evaporation.	Corn (Pride of Saline).		Feterita.	
		Turgid.	Wilted.	Turgid.	Wilted.
JULY 8.	*Cc.*				
7 to 9 a. m.	3.2	58.7	17.8	47.0	61.2
9 to 11 a. m.	4.4	56.9	28.0	159.8	100.5
11 to 1 p. m.	5.2	104.9	40.8	150.4	61.2
1 to 3 p. m.	5.0	80.0	20.3	136.3	70.0
3 to 5 p. m.	4.2	80.0	7.6	117.5	87.4
5 to 7 p. m.	3.6	60.5	7.6	61.1	43.7
JULY 14.					
7 to 9 a. m.	1.1	67.6	45.8	79.9	74.3
9 to 11 a. m.	3.3	106.7	30.5	141.0	65.6
11 to 1 p. m.	3.8	117.4	25.5	164.5	65.6
1 to 3 p. m.	4.0	154.7	40.8	164.5	122.4
3 to 5 p. m.	....	115.6	25.5	145.7	87.4
5 to 7 p. m.	....	55.1	10.2	75.2	34.9

[1] Each temperature value recorded in this table is the average of 20 different determinations taken during the period indicated.

PART 2

Temperature of the air and the upper surface of the leaves (°C.).

Time.	Evaporation.	Temperature of air.	Soybeans, Medium Yellow. Turgid.	Soybeans, Medium Yellow. Wilted.
JULY 13.	*Cc.*			
9.30 to 10 a. m.	0.6	34.3	35.6	39.2
11.10 to 11.30 a. m.	.7	34.3	34.5	38.9
1.10 to 1.40 p. m.	.8	29.5	29.2	32.0
3.20 to 3.45 p. m.	.7	35.9	35.6	38.9

Time.	Evaporation.	Temperature of air.	Cowpeas, New Era. Turgid.	Cowpeas, New Era. Wilted.
JULY 13.	*Cc.*			
10 to 10.30 a. m.	0.6	32.8	35.0	38.5
11.35 to 12 m.	.6	34.7	36.5	39.5
1.45 to 2.15 p. m.	1.1	37.8	38.3	44.4
2.25 to 2.50 p. m.	1.1	39.4	40.5	45.0
3.50 to 4.10 p. m.	.9	36.1	36.3	41.2

Rate of transpiration (gm²h).

Time	Evaporation.	Soybeans, Medium Yellow. Turgid.	Soybeans, Medium Yellow. Wilted.	Cowpeas, New Era. Turgid.	Cowpeas, New Era. Wilted.
JULY 13.	*Cc.*				
7 to 9 a. m.	1.4	45.1	15.1	32.2	24.7
9 to 11 a. m.	2.8	64.9	33.9	83.9	21.6
11 to 1 p. m.	3.3	68.5	22.6	81.8	14.7
1 to 3 p. m.	4.3	104.6	60.3	103.3	37.1
3 to 5 p. m.	3.5	82.9	11.2	71.0	6.2
5 to 7 p. m.	1.8	28.8	7.5	19.3	3.1

PART 3

Temperature of the air and the upper surface of the leaves (°C.).

Time.	Evaporation.	Temperature of air.	Plant. Corn (Pride of Saline).	Plant. Milo Dwarf.
JULY 18.	*Cc.*			
9.25 to 9.40 a. m.	0.6	27.5	28.3	27.5
11.15 to 11.30 a. m.	.5	29.3	29.9	29.6
1.10 to 1.25 p. m.	.9	32.4	32.1	31.9
3.10 to 3.27 p. m.	1.3	32.3	32.1	31.6
5.50 to 6.05 p. m.	.3	26.8	26.2	26.1
7.20 to 7.40 p. m.	.1	22.2	21.3	21.5

Time.	Evaporation.	Temperature of air.	Plant. Soybeans (Medium Yellow).	Plant. Cowpeas (New Era).
JULY 18.	*Cc.*			
9.45 to 10.10 a. m.	0.8	28.4	28.4	28.6
11.35 to 11.55 a. m.	.9	30.7	30.7	30.4
2 to 2.20 p. m.	1.4	32.8	33.5	32.5
3.40 to 4.00 p. m.	.7	33.0	33.0	33.1
6.10 to 6.25 p. m.	.4	25.9	25.8	25.3
7.45 to 8 p. m.	.05	21.9	21.3	21.3

Rate of transpiration (gm²h).

Time.	Evaporation.	Plant. Corn (Pride of Saline).	Plant. Milo Dwarf.	Plant. Soybeans (Medium Yellow).	Plant. Cowpeas (New Era).
JULY 18.	*Cc.*				
7 to 9 a. m.	1.6	57.7	51.1	49.6	44.6
9 to 11 a. m.	3.5	96.1	86.8	63.8	44.6
11 to 1 p. m.	4.7	123.1	122.5	105.1	114.1
1 to 3 p. m.	5.7	134.6	131.1	117.4	114.1
3 to 5 p. m.	4.8	111.6	115.7	68.3	79.3
5 to 7 p. m.	2.5	51.9	27.2	36.8	34.7

TABLE IV.—*Comparison of the temperature of the leaves and the hourly rate of transpiration of plants under optimum and limited water supply*—Continued

PART 4

Temperature of the air and the upper surface of the leaves (°C.).

Time.	Evaporation.	Temperature of air.	Corn (Freed White Dent). Turgid.	Corn (Freed White Dent). Wilted.
JULY 20.	*Cc.*			
10.20 to 10.40 a. m.	0.6	30.7	30.8	32.2
12.25 to 12.40 p. m.	.7	31.4	30.6	31.5
1.35 to 1.50 p. m.	.6	33.2	32.5	34.2
2.50 to 3.05 p. m.	.6	34.3	34.7	36.8
3.40 to 3.55 p. m.	.6	33.4	34.0	36.8
JULY 21.				
9.20 to 9.45 a. m.	.3	29.0	28.9	29.0
11.18 to 11.33 a. m.	.6	32.4	32.6	34.8

Time.	Evaporation.	Temperature of air.	Milo Dwarf Yellow. Turgid.	Milo Dwarf Yellow. Wilted.
JULY 20.	*Cc.*			
10.40 to 11.00 a. m.	0.7	31.9	32.0	33.6
12.40 to 1 p. m.	.6	32.1	31.9	34.1
1.55 to 2.10 p. m.	.6	34.0	35.1	36.5
2.30 to 2.45 p. m.	.7	34.7	34.6	37.6
4 to 4.20 p. m.	.5	32.9	33.8	35.8
JULY 21.				
9.50 to 10.05 a. m.	.3	28.8	28.8	29.4
10.35 to 10.50 a. m.	.4	32.3	32.9	35.1
11.35 to 11.50 a. m.	.6	33.8	33.8	37.3

Rate of transpiration (gm²h).

Time.	Evaporation.	Corn (Freed White Dent). Turgid.	Corn (Freed White Dent). Wilted.	Milo Dwarf Yellow. Turgid.	Milo Dwarf Yellow. Wilted.
JULY 20.	*Cc.*				
7 to 9 a. m.	2.3	59.7	62.8	49.4	2.2
9 to 11 a. m.	4.1	125.7	83.8	122.6	26.5
11 to 1 p. m.	5.0	135.1	80.8	117.1	31.0
1 to 3 p. m.	5.0	185.4	89.8	135.4	13.2
3 to 5 p. m.	4.8	216.3	59.8	95.1	8.8
5 to 7 p. m.	3.4	59.7	35.9	49.4	4.4
JULY 21.					
7 to 9 a. m.	1.4	12.5	5.9	9.1	13.2
9 to 11 a. m.	2.8	115.1	29.9	87.8	17.7
11 to 12 a. m.	2.5	163.4	83.8	109.8	17.7

PART 5

Temperature of the air and the upper surface of the leaves (°C.).

Time.	Evaporation.	Temperature of air.	Cowpeas (New Era).	
			Turgid.	Wilted.
JULY 24.	*Cc.*			
1.35 to 1.55 p. m.	.5	33.0	32.9	35.7
4.50 to 5.05 p. m.	.4	30.0	29.4	[illegible]
JULY 25.				
9.55 to 10.10 a. m.	.5	32.2	31.4	34.8
JULY 28.				
11.30 to 11.45 a. m.	1.0	37.1	36.1	41.9
1.15 to 1.30 p. m.	1.0	37.6	37.2	43.7
2.40 to 2.50 p. m.	.5	36.6	36.1	41.9

Time.	Evaporation.	Temperature of air.	Soybeans (medium yellow).	
			Turgid.	Wilted.
JULY 24.	*Cc.*			
3.40 to 3.55 p. m.	0.6	32.9	34.1	37.3
4.30 to 4.45 p. m.	.5	31.2	31.7	34.3
JULY 25.				
9.25 to 9.40 a. m.	.4	32.1	32.4	34.4
JULY 28.				
1.45 to 1.55 p. m.	.7	37.8	38.7	40.7
2.55 to 3.05 p. m.	.5	36.0	37.7	39.0

Rate of transpiration (gm³h).

Time.	Evaporation.	Cowpeas (New Era).		Soybeans (medium yellow).	
		Turgid.	Wilted.	Turgid.	Wilted.
JULY 24.	*Cc.*				
1 to 3 p. m.	3.1	69.8	32.0	82.6	26.2
3 to 5 p. m.	4.1	78.3	44.8	92.2	24.0
5 to 7 p. m.	1.6	57.9	25.6	39.6	13.1
JULY 25.					
7 to 9 a. m.	1.1	20.4	19.2	21.4	10.9
9 to 11 a. m.	2.8	71.5	12.8	64.3	15.3
11 to 1 p. m.	2.5	74.9	22.4	64.3	8.7
JULY 28.					
11 to 1 p. m.	....	126.0	6.3	75.1	4.3
1 to 3 p. m.	....	165.2	9.6	92.9	4.3

TABLE IV.—*Comparison of the temperature of the leaves and the hourly rate of transpiration of plants under optimum and limited water supply*—Continued

PART 6

Temperature of the air and the upper surface of the leaves (°C.).										Rate of transpiration (gm²h).					
Time.	Evaporation.	Temperature of air.	Corn (Freed White Dent).		Time.	Evaporation.	Temperature of air.	Milo (dwarf yellow.)		Time.	Evaporation.	Corn (Freed White Dent).		Milo (dwarf yellow).	
			Turgid.	Wilted.				Turgid.	Wilted.			Turgid.	Wilted.	Turgid.	Wilted.
AUG. 4.	*Cc.*				AUG. 4.	*Cc.*				AUG. 4.	*Cc.*				
8 to 8.15 a. m.	0.05	23.7	23.7	24.0	8.25 to 8.40 a. m.	0.1	25.5	25.3	25.5	7 to 9 a. m.	0.6	20.4	18.9	26.2	31.6
9.10 to 9.25 a. m.	.2	25.7	25.4	25.8	9.30 to 9.45 a. m.	.2	26.0	25.9	26.2	9 to 11 a. m.	2.1	68.8	30.8	45.4	37.9
11.10 to 11.20 a. m.	.3	29.1	28.2	30.4	11.20 to 11.35 a. m.	.5	30.5	31.0	32.2	11 to 1 p. m.	3.7	135.1	37.9	64.6	28.4
1.30 to 1.45 p. m.	.5	29.2	28.7	29.5	2.00 to 2.15 p. m.	.4	30.3	30.5	32.4	1 to 3 p. m.	3.6	81.5	28.4	52.4	25.2
3.45 to 4 p. m.	.4	28.1	27.5	28.3	4.05 to 4.20 p. m.	.4	28.6	28.2	28.8	3 to 5 p. m.	2.3	61.0	14.2	52.4	25.2
6.45 to 6.55 p. m.	.2	25.0	24.7	24.8	4.30 to 4.45 p. m.	.4	31.0	31.5	33.6	5 to 7 p. m.	2.0	30.5	21.3	17.4	22.1
AUG. 5.					AUG. 5.					AUG. 5.					
9.10 to 9.25 a. m.	.3	28.3	28.0	29.2	9.45 to 10.00 a. m.	.4	28.9	28.9	31.5	7 to 9 a. m.	1.2	33.1	14.2	43.7	15.8
10.05 to 10.20 a. m.	.6	31.3	31.6	35.2	11.15 to 11.25 a. m.	.3	32.5	32.0	33.5	9 to 11 a. m.	3.3	107.0	33.1	83.9	25.2
11.05 to 11.15 a. m.	.4	32.3	31.2	35.5	1.50 to 2.15 p. m.	.8	33.9	34.1	37.8	11 to 1 p. m.	4.7	173.3	33.1	97.9	41.1
1.25 to 1.45 p. m.	.7	33.6	33.6	37.0	3.10 to 3.30 p. m.	.6	33.3	32.2	36.4	1 to 3 p. m.	4.6	147.8	37.9	117.1	12.6
3.50 to 4.05 p. m.	.4	33.6	33.3	35.8	6.35 to 6.50 p. m.	.2	28.6	28.1	28.3	3 to 5 p. m.	4.4	132.5	33.1	104.9	34.7
6.20 to 6.35 p. m.	.2	28.7	28.2	28.6						5 to 7 p. m.	2.3	45.8	4.7	17.4	6.3

PART 7

Temperature of the air and the upper surface of the leaves (°C).

Time.	Evaporation.	Temperature of air.	Corn (Kansas Sunflower). Turgid.	Corn (Kansas Sunflower). Wilted.
AUG. 7.	*Cc.*			
8.20 to 8.35 a. m.	0.3	24.0	24.0	24.1
10.00 to 10.15 a. m.	.6	28.3	28.7	29.8
11.10 to 11.18 a. m.	.6	29.8	29.9	31.4
1.30 to 1.45 p. m.	1.0	31.0	30.8	31.5
3.15 to 3.30 p. m.	.6	31.5	31.4	32.8
6.30 to 6.42 p. m.	.3	24.5	24.2	24.4
6.45 to 7.00 p. m.	.2	23.7	23.4	23.7
AUG. 8.				
7.50 to 8.00 a. m.	.1	22.4	22.9	23.4
10.05 to 10.20 a. m.	.6	27.5	28.0	29.0
11.15 to 11.30 a. m.	.7	28.3	29.3	30.6
1.30 to 1.45 p. m.	.8	30.3	31.1	32.2
6.35 to 6.47 p. m.	.2	23.8	23.5	23.6

Time.	Evaporation.	Temperature of air.	Sorgo (Freed). Turgid.	Sorgo (Freed). Wilted.
AUG. 7.	*Cc.*			
8.40 to 8.50 a. m.	0.3	25.0	25.3	25.5
10.20 to 10.35 a. m.	.8	28.2	29.4	30.7
11.25 to 11.35 a. m.	.5	29.5	28.9	31.0
2.00 to 2.15 p. m.	.6	30.4	30.2	31.9
3.35 to 3.50 p. m.	.6	31.8	31.5	33.5
AUG. 8.				
8.05 to 8.20 a. m.	.1	23.5	24.5	25.1
10.25 to 10.40 a. m.	.6	27.7	28.1	29.1
1.50 to 2.05 p. m.	.6	30.5	30.4	32.2
6.50 to 6.58 p. m.	.1	23.2	22.8	23.1

Rate of transpiration (gm²h).

Time.	Evaporation.	Corn (Kansas Sunflower). Turgid.	Corn (Kansas Sunflower). Wilted.	Sorgo (Freed). Turgid.	Sorgo (Freed). Wilted.
AUG. 7.	*Cc.*				
7 to 9 a. m.	1.1	31.7	29.5	62.4	70.2
9 to 11 a. m.	4.6	108.4	105.8	158.2	175.7
11 to 1 p. m.	6.3	136.5	66.4	179.1	35.1
1 to 3 p. m.	6.2	119.6	34.4	158.2	70.2
3 to 5 p. m.	4.8	72.9	39.3	124.9	35.1
5 to 7 p. m.	3.6	16.8	7.3	87.4	11.7
AUG. 8.					
7 to 9 a. m.	.9	37.4	22.1	49.9	11.7
9 to 11 a. m.	4.3	67.3	34.4	99.8	29.2
11 to 1 p. m.	5.4	78.5	29.5	158.2	29.2
1 to 3 p. m.	5.9	82.2	29.5	170.7	46.8
3 to 5 p. m.	4.7	86.0	29.5	170.7	46.8
5 to 7 p. m.	3.0	29.9	9.8	49.9	23.4

The maximum temperature difference observed between the turgid and wilted leaves of corn exposed to the direct rays of the sun was 4.3° C. This temperature value is the average of 20 determinations made during a 10-minute period from 11.05 to 11.15 a. m., when the average temperature of the air for the period was 32.3° C., and the transpiration rate from the turgid plants was approximately five times that from the wilted plants. The average temperature of the turgid and wilted leaves for more than 600 determinations during the hours of 9 a. m. to 4 p. m. over a period of eight days during the months of July and August was 30.65° and 32.5°, respectively. Thus the average temperature of the wilted leaves of corn was 1.85° C. higher than that of the turgid leaves, under the conditions prevailing during the experiments. The average temperature of the air during these experimental periods was 30.65° C., while the average transpiration rate for the turgid plants was 105.3 gm^2h as compared to 43.2 gm^2h from the wilted plants.

The average transpiration rate of the turgid and wilted sorghum plants from 9 a. m. to 4 p. m. over a period of eight days was 110.9 gm^2h and 45.6 gm^2h, respectively. The average of 650 temperature determinations of turgid and wilted leaves during that period was respectively 30.77° C. and 32.32° C., while the temperature of the air averaged 30.75° C. The temperature of the wilted leaves under these conditions averaged 1.55° C. higher than that of the turgid leaves.

In the experiments with soybeans, the average rate of transpiration from the turgid plants was 70.5 gm^2h and from the wilted plants 20.5 gm^2h, while the average temperature of the air was 34.1° C. Under these conditions the average temperature for 200 determinations over a period of four days in July, when the plants had reached their full vegetative growth, was 37.5° C. for the wilted leaves and 34.7° C. for the turgid leaves. The average temperature of the wilted leaves was thus 2.8° C. higher than that of the turgid leaves.

The average temperature of the air during the experiments with cowpeas was 35.7° C. and the transpiration rate of the turgid plants was 3.5 times that of the wilted plants. The average temperature of the turgid leaves for 200 observations was 36° C., while that of the wilted leaves was 40.65° C. The average difference in temperature between the turgid and wilted leaves of cowpeas was 4.65° C. This was the greatest average difference observed in the experiments with these four species of plants. The maximum temperature difference observed between the wilted and turgid leaves of cowpeas was 6.7° C. during a 15-minute period from 1.15 to 1.30 p. m., when the temperature of the air was 37.6° C. and the transpiration rate of the wilted plant was approximately only one-sixteenth that of the turgid plants.

The observations upon the plants just mentioned show that the temperature of a wilted leaf in direct sunlight is always higher than the temperature of a turgid leaf exposed to the same conditions. The average temperature of the wilted leaves of corn, sorghum, soybean, and cowpeas during the hours of 9 a. m. and 4 p. m. was respectively 1.85°, 1.55°, 2.8°, and 4.65° C. higher than that of the turgid leaves. These differences in temperature are not striking, and it would seem doubtful whether the increased temperature of the wilted leaves, with the possible exception of the case of cowpeas, could to any marked degree injure the protoplasm or even retard its vital activities. We need to know more, however, about the effect of temperature upon the protoplasm of these plants before any definite statements can be made con-

erning the influence of these observed differences in temperatures upon he life processes in the leaves.

The temperature of the air during these observations on the relationhip of the transpiration rate and temperatures of leaves ranged from 9° to 38° C. The climatic conditions during July and August, 1922, vere comparatively mild, so that the maximum temperature of the air luring the experiments was from 2° to 6° C. lower than that commonly experienced during the most severely hot part of the growing season in Kansas. The data presented, however, are believed to represent the temperature relationships of the wilted and turgid leaves of plants under the conditions in the field. An increase in the temperature of the air of from 2° to 6° C. would not materially alter the above-observed temperature differences between wilted and turgid leaves, since, as discussion will show later, the heat absorbed by the type of leaves used in these experiments is quickly dissipated, so that their temperature rises to only a few degrees above that of the surrounding air. The temperature of the wilted leaves during the early morning and evening hours and during the night rapidly drops to that of the turgid leaves, which is approximately the temperature of the surrounding air.

LEAF TEMPERATURE DURING THE DAY AND NIGHT

The greater number of the 20,000 determinations of the relative temperature of the air and leaves that are herein reported was made upon the upper surfaces of the turgid leaves of plants during the daylight hours from 9 a. m. to 4 p. m. The plants upon which the observations were made included four varieties of sorghum and one variety each of watermelon, pumpkin, cowpea, soybean, and alfalfa. The average of 1,000 temperature observations of the air and of the upper surface of the turgid leaves of corn in direct sunlight and under a wide range of atmospheric conditions was 30.58° C. for the air and 30.64° C. for the leaves. The average of the same number of determinations made with the leaves of five sorghum varieties, under conditions of exposure to the sun similar to those of the corn leaves, showed that the temperature of the leaves was 30.64° C., while the average of an equal number of determinations of the air temperature during the same period was 30.66° C. Five hundred observations on soybeans gave an average temperature of the air of 33.13° C., and an average of 33.66° C. for the temperature of the upper surface of the leaves, while a similar number of determinations on the leaves of cowpeas showed an average temperature of 34.4° C., and the temperature of the air averaged 34.2° during the observations. The determinations made upon the leaves of the pumpkin and watermelon were few in number, but the data obtained showed that the average temperature of the upper surface of the leaves of these plants was approximately the same as that of the surrounding air. The average of about 200 temperature determinations on the leaves of alfalfa was 27.8° C., while the air temperature averaged 28.6° C.

These observations show that the temperature of the turgid leaves of corn, sorghum, pumpkin, watermelon, and soybean in direct sunlight, under the general climatic conditions which prevail during the growing season in Kansas, fluctuates slightly above and below air temperature, but that the average temperature is the same as that of the surrounding air. The temperature of the leaves of cowpeas and alfalfa under the same conditions as those of the other plants consistently showed a temperature of less than 1° C. below that of the surrounding air. These

results indicate that in the case of corn, sorghum, watermelon, pumpkin, and soybean the heat absorbed by the leaf from the sun is quickly utilized in transpiration and rapidly disseminated into the surrounding air, so that the temperature of the leaves is always approximately that of the air. In the case of the leaves of cowpea and alfalfa the rate of transpiration is evidently rapid enough to reduce the temperature of the leaf slightly below that of the air.

The results obtained in these experiments are in considerable contrast to those previously reported by several investigators. Askenasy (*1*) by placing a thermometer in close contact with the surface of the fleshy leaves of three species of Sempervivum found that they attained a temperature in the sunlight of 18° to 25° C. above that of the surrounding air. Under the same conditions, however, he found that the leaves of *Aubrietia deltoidea* and *Gentiana cruciata* showed a temperature of only 4° to 7° C. above that of the air temperature. He attributed the high temperature of the fleshy leaves of Sempervivum to the fact that they carried on little transpiration and that the heat they absorb is not readily dissipated by air currents or radiation. These observations on the temperature of the leaves of Sempervivum were later verified by Ursprung (*15*). Blackman and Matthaei (*2*) by means of a thermoelectrical method found that the internal temperature of detached leaves of cherry laurel in direct sunshine was from 4° to 13° C. above that of the air temperature, the difference depending upon the position of the leaf relative to the rays of the sun and the time of day that the observations were made. Brown and Escombe (*3, p. 83–85*) indirectly calculated the temperature of the leaves of several plants from certain known energy relations between the leaf and the air. In the case of the sunflower the leaves showed a temperature of 17.3° C. when the air temperature was 16.9° C., and when the air temperature was 27.2 °C. the calculated temperature of the leaf was 25.4° C. Smith (*14*), using the modified thermoelectrical method of Matthaei (*8*) upon insolated leaves in the Tropics, found that the internal temperature of leaves of various types was 15° C. above that of the surrounding air, when the temperature of the latter was 25° to 28° C. Seeley (*10*) obtained the temperature of the leaves of the garden strawberry by folding the leaf around the bulb of a thermometer The temperature of the leaves obtained in this manner on clear days averaged 15° F. higher than the temperature of the air in a weather instrument shelter near by.

In determining the temperature of a leaf, the atmospheric conditions surrounding it must always be taken into consideration. A leaf in direct sunshine freely exposed to a breeze always has a lower temperature than one under like conditions of sunlight but in such a position as to be protected from air currents. It seems probable that the relatively high temperature of the leaves above that of the air surrounding them, as reported by Blackman and Matthaei and by Smith, was due to the fact that the leaves were boxed in by the apparatus used, so that the absorbed heat could not readily be disseminated. Under such conditions one would expect a much higher temperature for the leaves than if they were exposed to the freely circulating air. Smith (*14*) finds from his observations that breezes reduce the temperature of the leaves in sunlight by amounts varying from 2° to 10° C., and that a thin leaf is much more noticeably affected than a thick one.

When the atmospheric conditions during the day are comparatively mild and the rate of evaporation low, the leaves of most of the plants

examined show a temperature slightly lower than that of the surrounding air. This fact is shown by the leaves of corn and the sorghums in one or two examples in Tables IV and V. The effect of mild climatic con-

TABLE V.—*Temperature of the upper surface of the leaves of plants during the day and night*

PART 1

Time.	Evaporation.	Number of determinations.	Average temperature (°C.) of—				
			Air.	Corn, Pride of Saline.	Milo, Dwarf.	Cowpeas, New Era.	Soybeans, Medium Yellow.
July 18:	*Cc.*						
9.25 to 9.40 a. m.	0.6	20	27.5	28.3	27.5		
9.45 to 10.10 a. m	.8	20	28.4			28.7	28.5
11.15 to 11.30 a.m.	.8	20	29.3	29.9	29.5		
11.35 to 11.55 a.m.	.9	20	30.7			30.4	30.6
1.10 to 1.25 p. m.	.9	20	32.4	31.9	32.1		
2.00 to 2.20 p. m.	1.4	20	32.7			32.4	33.5
3.10 to 3.27 p. m.	1.3	20	32.3	32.1	31.6		
3.40 to 4.00 p. m.	.7	20	33.0			33.1	33.0
5.50 to 6.05 p. m.	.4	20	26.8	26.2	26.1		
6.10 to 6.25 p. m.	.3	20	26.9			25.8	25.3
7.20 to 7.40 p. m.	.1	20	22.2	21.3	21.5		
7.45 to 8.00 p. m.	.05	20	21.9			21.4	21.4
9.00 to 9.20 p. m.	.05	10	19.5			19.7	19.6
9.25 to 9.40 p. m.	(1)	10	19.4	19.1	19.1		
11.00 to 11.25 p.m.	(1)	10	17.9	17.7	17.9		
11.30 to 11.40 p.m.	(1)	10	17.5			17.5	17.5
July 19:							
1.05 to 1.15 a. m.	(1)	10	17.3			17.3	17.3
1.20 to 1.30 a. m.	(1)	10	17.2	17.0	17.1		
3.10 to 3.20 a. m.	(1)	10	16.6	16.5	16.6		
3.30 to 3.40 a. m.	(1)	10	16.5			16.6	16.6
5.05 to 5.15 a. m.	(1)	10	16.2			16.2	16.0
5.15 to 5.25 a. m.	(1)	10	16.1	16.0	16.0		
7.00 to 7.10 a. m.	(1)	10	20.5	20.6	20.5		
7.12 to 7.22 a. m.	(1)	10	20.7			20.4	20.5

PART 2

Time.	Evaporation.	Number of determinations.	Average temperature (°C.) of—				
			Air.	Cowpeas, New Era.	Pumpkin, Cheese.	Watermelon, Cobs Gem.	Sudan grass.
July 26:	*Cc.*						
10.10 to 10.20 a.m.	0.3	10	35.0	35.0	35.3		
11.25 to 11.35 a.m.	.4	10	37.6			39.8	37.8
1.08 to 1.18 p. m.	.4	10	35.1	35.3	35.5		
8.05 to 8.15 p. m.	.1	10	24.2			24.0	24.1
8.20 to 8.30 p. m.	.1	10	22.8	22.6	22.5		
10.10 to 10.20 p.m.	(1)	10	21.8	21.8	21.5		
10.30 to 10.40 p.m.	(1)	10	21.7			21.6	21.6
July 27:							
12.20 to 12.30 a.m.	(1)	10	22.1			22.1	22.1
12.35 to 12.45 a.m.	(1)	10	22.1	21.8	21.8		
2.10 to 2.20 a. m.	(1)	10	21.8	21.7	21.7		
2.20 to 2.30 a. m.	(1)	10	21.8			21.7	21.9
4.10 to 4.20 a. m.	(1)	10	21.1			21.1	21.4
4.20 to 4.30 a. m.	(1)	10	21.0	20.7	20.8		
6.05 to 6.15 a. m.	(1)	10	20.6	20.3	20.2		
6.20 to 6.30 a. m.	(1)	10	21.3			20.9	21.2

[1] No evaporation.

TABLE V.—*Temperature of the upper surface of the leaves of plants during the day and night*—Continued

PART 3

Time.	Evaporation.	Number of determinations.	Average temperature (°C.) of— Air.	Kafir, Pink. Turgid.	Kafir, Pink. Wilted.	Corn, Commercial White. Turgid.	Corn, Commercial White. Wilted.
	Cc.		°				
Aug. 17:							
8.40 to 8.55 a. m.	0.4	20	30.1	29.8	29.8	....	....
9.20 to 9.35 a. m.	.4	20	31.3	31.2	32.2	....	....
9.55 to 10.05 a. m.	.6	20	33.1	32.6	33.4	....	....
11.00 to 11.15 a. m.	.8	20	34.0	33.5	35.0	....	....
11.15 to 11.30 a. m.	.9	20	34.3	33.7	35.1	....	....
1.25 to 1.40 p. m.	1.0	20	35.0	33.6	35.6	....	....
2.05 to 2.20 p. m.	1.0	20	35.5	35.0	36.8	....	....
3.10 to 3.25 p. m.	1.0	20	35.1	33.8	35.7	....	....
3.30 to 3.50 p. m.	1.3	20	36.2	34.8	36.7	....	....
4.35 to 4.50 p. m.	1.0	20	35.6	33.8	35.6	....	....
6.55 to 7.10 p. m.	.4	20	29.1	28.2	28.6	....	....
Aug. 18:							
8.30 to 8.45 a. m.	.4	20	31.7	....	....	31.9	32.6
9.20 to 9.35 a. m.	.5	20	33.2	....	....	33.4	35.4
10.00 to 10.15 a. m.	.8	20	34.2	....	....	33.3	36.2
11.05 to 11.20 a. m.	.8	20	34.3	....	....	33.5	37.4
1.30 to 1.45 p. m.	.9	20	36.9	....	....	36.3	39.0
2.55 to 3.10 p. m.	1.1	20	35.8	....	....	35.1	38.1
3.40 to 3.55 p. m.	.9	20	33.6	....	....	33.1	35.2
4.10 to 4.25 p. m.	.8	20	32.5	....	....	32.4	34.3
4.35 to 4.50 p. m.	.6	20	30.7	....	....	30.3	30.5
6.30 to 6.45 p. m.	.3	20	28.0	....	....	27.5	27.7
7.00 to 7.15 p. m.	.2	20	27.2	26.9	26.9	....	....
8.55 to 9.10 p. m.	.2	20	26.2	26.0	26.0	....	....
9.15 to 9.30 p. m.	.1	20	25.4	....	....	25.0	25.1
11.05 to 11.20 p. m.	.1	20	23.1	....	....	22.7	22.8
11.25 to 11.40 p. m.	.1	20	23.0	22.8	22.8	....	....
Aug. 19:							
1.05 to 1.20 a. m.	.1	20	22.7	22.5	22.5	....	....
1.25 to 1.40 a. m.	.1	20	22.7	....	....	22.3	22.5
3.00 to 3.15 a. m.	.1	20	21.2	....	....	20.8	21.0
3.20 to 3.35 a. m.	.1	20	21.2	20.9	21.0	....	....

ditions upon the temperature of leaves is further shown when their temperature is observed from 4 p. m. until twilight and from daylight until 8 a. m. The temperature of leaves during these periods is always lower than that of the surrounding air and is plainly evident in any of the tables where any temperature data on leaves for these periods are recorded. During the night, according to our observations, the temperature of the leaves is approximately that of the air. Some of the data obtained on the temperature of leaves during the day and night are recorded in Table V. The behavior of the temperature of corn and milo leaves during a 24-hour period is illustrated by graphs in figure 5. The observations are similar to those of Shreve (*11*), who measured the temperature of the leaves of *Parkinsonia microphylla* by a calorimetric method. She found that the temperature curves of the leaves were below the air temperature curves at night and in early morning until about 10 o'clock, when the leaf temperature rose above the air temperature, retaining that relative position until shortly after noon.

TEMPERATURE OF DIFFERENT PORTIONS OF THE LEAF

Some determinations were made to compare the temperature of the base and tip of the leaves of cowpea, soybean, velvet bean, Sudan grass, Blackhull kafir and two varieties of corn under conditions of direct and diffuse sunlight. The conditions necessary to produce diffuse light were obtained by the opportune passing of clouds over the sun or by shading the plant, or the portion of it under observation, by an ordinary umbrella. The data obtained from these experiments are shown in Table VI. The experiments with these leaves in direct sunlight show that the temperature of the base of the leaf is always consistently lower than that of its tip. The differences in temperature observed varied from 0.1° to 1.5° C., depending evidently upon the nature of the leaf and upon the available water supply. In diffuse light the temperature differences between the two portions were smaller than those observed in direct light, and in a few cases no differences in temperature were found.

TABLE VI.—*Difference in temperature of the upper surface of the base and tip of the leaves of various plants*

Time.	Kind of plant.	Number of determinations.	Condition.	Average temperature of— Air.	Base.	Tip.
				°C.	°C.	°C.
Aug. 12:						
2.35 to 2.50 p. m.	Cowpeas, Victor	20	In sunshine	35.5	35.4	36.8
2.55 to 3.10 p. m.	do	20	Shaded	34.0	33.7	33.8
3.45 to 4.00 p. m.	Soybeans, Morse	20	In sunshine	35.9	37.0	37.2
4.15 to 4.30 p. m.	do	20	Shaded	33.0	32.8	32.8
Aug. 14.						
10.05 to 10.20 a. m.	Kafir, Blackhull	20	do	31.4	30.6	30.8
10.25 to 10.40 a. m.	do	20	In sunshine	33.2	33.2	33.4
2.20 to 2.35 p. m.	Sudan grass	20	do	33.1	32.6	32.7
2.55 to 3.10 p. m.	do	20	Shaded	32.9	32.5	32.6
3.45 to 4.00 p. m.	Corn, Reid Yellow Dent	20	In sunshine	35.4	36.4	37.3
4.10 to 4.25 p. m.	do	20	Shaded	32.2	31.9	32.1
Aug. 15:						
10.50 to 11.05 a. m.	Corn, Commercial White	20	In sunshine.	32.2	32.0	32.5
11.10 to 11.25 a. m.	do	20	Shaded	30.2	29.9	30.1
2.10 to 2.25 p m.	do	20	Clouds	30.7	30.0	30.0
Aug. 16:						
10.05 to 10.20 a. m.	Bean, Velvet	20	Shaded	30.6	30.1	30.2
10.25 to 10.40 a. m.	do	20	In sunshine	32.1	32.1	32.4
10.55 to 11.10 a. m.	do	20	Shaded	32.2	31.6	31.7
11.10 to 11.25 a. m.	do	20	Clouds	30.5	30.3	30.4
1.30 to 1.50 p. m.	Cowpeas, Victor	20	In sunshine	35.1	36.8	37.2
1.55 to 2.10 p. m.	do	20	Shaded	35.6	35.0	35.0
3.30 to 3.45 p. m.	Soybeans, Morse	20	In sunshine	34.4	34.3	34.4
3.50 to 4.05 p. m.	do	20	Shaded	34.0	33.8	33.8

It would seem that this temperature difference between the two regions of the leaf is due to a difference in the available water supply. Under conditions of relatively high evaporation the water supply entering the leaf may be so depleted by transpiration in the basal region that the tissue near the tip does not receive a supply of water adequate to maintain a transpiration rate equal to that of the lower portion of the leaf, and consequently the temperature of the tip is higher than that of the base. The fact that this difference in temperature diminishes or disappears entirely under the milder atmospheric conditions in diffuse light would seem to strengthen this interpretation of the results, but the relative rate of transpiration of the two regions of the leaf must be determined before any conclusions can be drawn.

The temperatures of the upper and lower surfaces of leaves were determined for a considerable number of different plants under conditions of both direct and diffuse light, as shown in Table VII. The temperature of the lower surface of leaves exposed to direct sunlight was always consistently lower than that of the upper surface, although the differences were always less than 1° C. It could not be determined whether this difference in temperature was due to a difference in the rate of transpiration of the two surfaces or whether it was caused by the upper surface being more highly heated on account of its more direct exposure to the rays of the sun. In diffuse light or during the early evening and morning hours little or no difference was observed between the temperature of the two leaf surfaces.

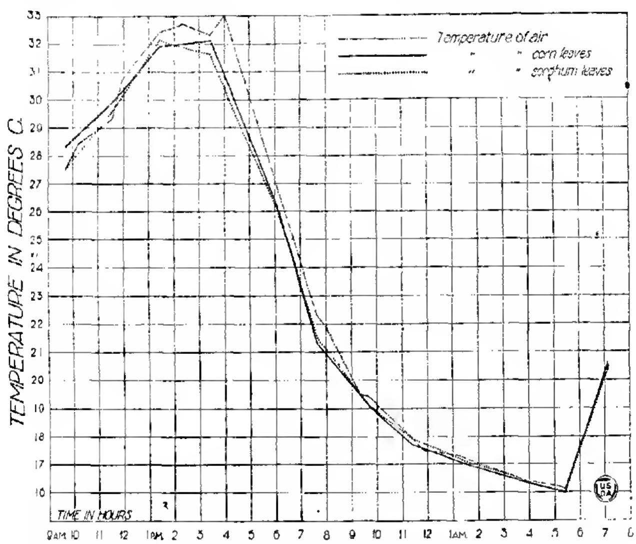


FIG. 5.—Graphs showing the temperature of the air and of the turgid leaves of Pride of Saline corn and Dwarf milo during the day and night July 18 and 19, 1922.

TEMPERATURE OF LEAVES IN DIRECT AND IN DIFFUSE SUNLIGHT

A study of the temperature of leaves in direct and in diffuse sunlight was made at various periods of the day upon three varieties of corn, four varieties of sorghum, and one variety each of cowpeas, soybean, velvet bean, alfalfa, watermelon, and pumpkin.

Some of the observations were made upon leaves in diffuse light which was artificially provided by shading the plant or some portion of it with an ordinary umbrella. The data obtained under these conditions are shown in Table VII. In a number of cases the passage of a heavy cloud over the sun in the middle of a series of determinations of leaf temperatures gave an opportunity to observe the behavior of the temperature of a leaf when its light exposure is suddenly changed from direct sunlight to diffuse light. The data for two series of observations of this kind are

TABLE VII.—*Average temperature of the upper and lower surfaces of the leaves of plants under different conditions of light intensity* [1]

Time.	Kind of plant.	Number of determinations.	Conditions.	Average temperature of— Air.	Upper.	Lower.
				°C.	°C.	°C.
June 15:						
9.30 to 10.00 a. m.	Feterita	20	In sunshine	27.6	26.8	26.5
July 3:						
10.05 to 10.20 a. m.	Cane, Freed	20	do		25.6	25.1
10.30 to 10.45 a. m.	Corn, Pride of Saline	20	do		25.7	25.4
July 26:						
10.40 to 11.00 a. m.	Cowpeas, New Era	10	Shaded	30.3	29.4	29.3
11.05 to 11.15 a. m.	Pumpkin, Cheese	10	do	30.9	29.9	30.0
1.20 to 1.30 p. m.	Cowpeas, New Era	10	In sunshine	35.1	35.1	34.4
1.35 to 1.45 p. m.	Pumpkin, Cheese	10	do	35.4	35.7	35.4
2.00 to 2.10 p. m.	Cowpeas, New Era	10	Shaded	31.9	30.8	30.7
2.15 to 2.25 p. m.	Pumpkin, Cheese	10	do	31.7	30.5	30.4
3.05 to 3.30 p. m.	Watermelon, Cobs Gem	20	In sunshine	35.4	35.9	35.1
3.45 to 3.55 p. m.	do	10	Shaded	29.4	28.5	28.5
4.05 to 4.20 p. m.	Sudan grass	10	In sunshine	30.6	30.6	30.2
4.30 to 4.40 p. m.	do	10	Shaded	28.7	27.7	27.7
6.10 to 6.20 p. m.	Cowpeas, New Era	10	In sunshine	28.2	27.1	27.1
6.30 to 6.40 p. m.	Watermelon, Cobs Gem	10	do	27.5	26.9	26.9
6.45 to 6.55 p. m.	Sudan grass	10	do	27.2	26.9	26.9
July 28:						
2.05 to 2.15 p. m.	Corn, Kansas Sunflower	10	do	35.4	34.9	34.7
2.20 to 2.30 p. m.	do	10	Shaded	34.3	33.8	33.8
Aug. 8:						
3.00 to 3.30 p. m.	Alfalfa, Common	20	In sunshine	26.4	25.8	25.7
3.40 to 3.55 p. m.	do	20	do	26.6	26.0	25.9
4.10 to 4.25 p. m.	do	20	do	26.6	26.1	26.0
Aug. 9:						
2.00 to 2.15 p. m.	do	20	do	30.7	29.7	29.5
2.20 to 2.35 p. m.	do	20	Shaded	29.1	28.3	28.3
Aug. 10:						
8.50 to 9.05 a. m.	do	20	In sunshine	26.7	26.4	25.8
9.10 to 9.25 a. m.	do	20	Shaded	26.0	25.2	25.1
10.10 to 10.25 a. m.	do	20	In sunshine	29.2	28.0	27.7
10.30 to 10.45 a. m.	do	20	Shaded	28.0	27.1	26.9
2.30 to 2.45 p. m.	do	20	In sunshine	32.5	31.6	31.3
2.55 to 3.10 p. m.	do	20	Shaded	30.3	29.1	29.0
Aug. 12:						
8.45 to 9.00 a. m.	do	20	In sunshine	27.7	26.8	26.6
9.02 to 9.15 a. m.	do	20	Shaded	26.5	25.6	25.5
Aug. 14:						
8.45 to 9.00 a. m.	Kafir, Blackhull	20	In sunshine	29.7	30.4	29.7
9.50 to 10.05 a. m.	do	20	Shaded	30.5	30.1	30.0
11.15 to 11.30 a. m.	do	20	In sunshine	32.0	32.6	32.2
1.40 to 1.55 p. m.	Sudan grass	20	do	32.5	32.4	32.1
4.40 to 4.55 p. m.	Corn (Reid Yellow Dent)	20	Shaded	30.4	30.3	30.3
Aug. 15:						
1.45 to 2.00 p. m.	Corn, Commercial White	20	In sunshine	32.9	32.1	31.7
Aug. 16:						
8.35 to 8.50 a. m.	Bean, Velvet	20	do	28.6	28.5	28.5
8.55 to 9.10 a. m.	do	20	Shaded	28.5	28.1	28.1
9.25 to 9.40 a. m.	do	20	In sunshine	29.3	29.6	29.6
9.45 to 10.00 a. m.	do	20	Shaded	30.2	29.9	29.9

[1] The conditions of diffuse light for the experiments reported in this table were obtained by shading the entire plant, or that portion of it under observation, by an ordinary umbrella.

given in Tables VIII and IX, and the results of the experiments are illustrated by graphs in figures 6 and 7. Some observations were made on the temperature of different leaves of the same plant, some of which were in direct sunlight and some shaded by other leaves of the plant. An example of the behavior of the temperature of the leaves of cowpeas under these conditions during a 20-minute period is shown in Table X, and is illustrated by graphs in figure 8. The data obtained show that in diffuse light the temperature of attached turgid leaves of the plants studied is always consistently lower than the temperature of the surrounding air. The average temperature differences between the turgid leaves and the surrounding air under conditions of diffuse light varied from 0.1° to 3° C. In a large number of cases the difference was less than

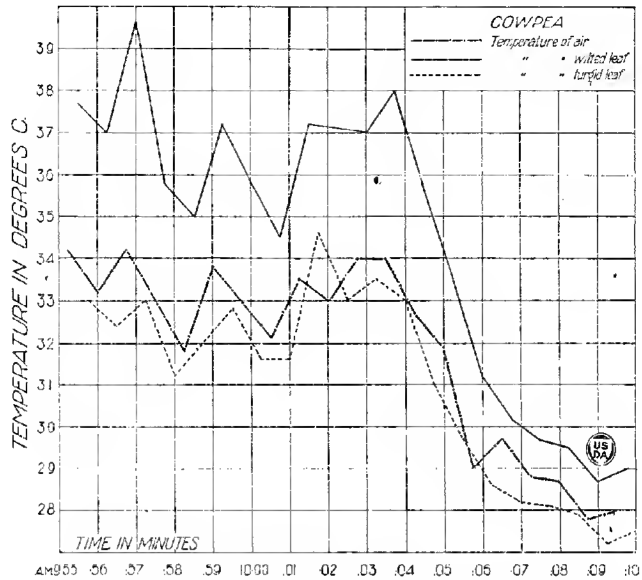


Fig. 6.—Graphs showing the effect of a cloud passing over the sun upon the temperature of the air and of the leaves of wilted and turgid plants. The cloud completely obscured the sun at 10.04 a. m., July 25, 1922.

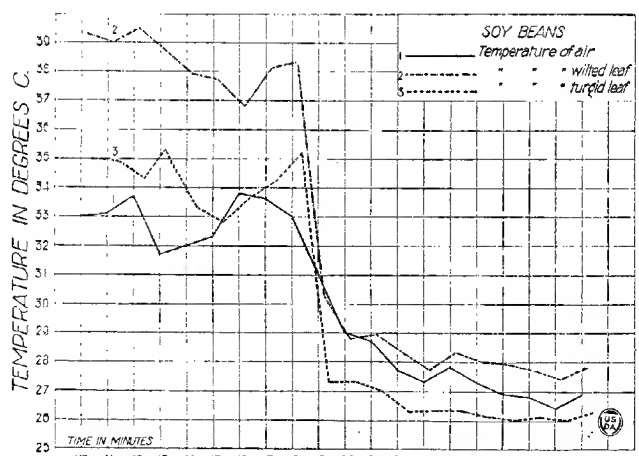
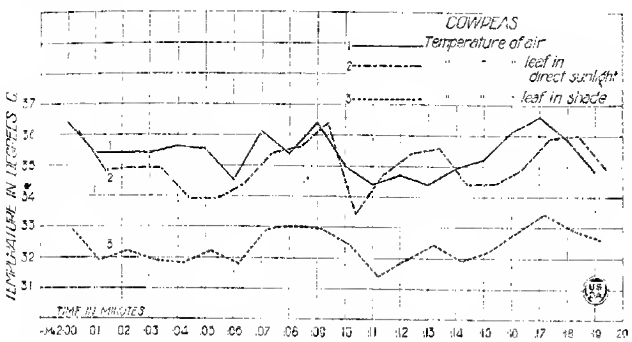


Fig. 7.—Graphs showing the effect of a cloud passing over the sun upon the temperature of the air and of the leaves of wilted and turgid plants. The cloud completely obscured the sun at 1.19 p. m., July 13, 1922.

° C., while in a few cases a maximum difference of 5° C. was observed. n direct sunlight the temperature of the turgid leaves of most plants uctuates above and below the air temperature, but as soon as a cloud bscures the sun the temperature of the leaf almost immediately drops elow the temperature of the air, as shown in figures 6 and 7. A study f these figures will also show that the difference in temperature between wilted leaf and a turgid leaf is not nearly so great in diffuse light as in irect sunlight.



.. 8.—Graphs showing the temperature of the air and of leaves in direct sunlight and in diffuse light from 2.00 p. m. to 2.20 p. m., July 24, 1922.

ABLE VIII.—*Temperature changes of the air and of the leaves of turgid and wilted soybean plants in direct sunshine and in diffuse light caused by a heavy cloud obscuring the sun*

IN DIRECT SUNLIGHT

Time.	Temperature of—		
	Air.	Turgid leaf.	Wilted leaf.
P. m.	° *C.*	° *C.*	° *C.*
1.10	32.0	34.0	38.3
1.11	32.1	33.9	38.0
1.12	32.7	33.3	38.5
1.13	30.7	30.7	34.3
1.14	31.0	32.3	36.9
1.15	31.3	31.8	36.7
1.16	32.8	32.6	35.8
1.17	32.6	33.2	37.1
1.18	32.0	34.2	37.3

IN DIFFUSE LIGHT, CLOUD OVER SUN

1.19	30.0	26.3	29.3
1.20	28.0	26.3	27.8
1.21	27.7	26.0	27.9
1.22	26.7	25.3	27.3
1.23	26.3	25.3	26.7
1.24	26.8	25.3	27.3
1.25	26.3	25.1	27.0
1.26	25.9	25.0	26.9
1.27	25.8	25.1	26.7
1.28	25.4	25.0	26.4
1.29	25.9	25.3	26.8

TABLE IX.—*Temperature changes of the air and of the leaves of turgid and wilted cowpea plants in direct sunlight and in diffuse light caused by a heavy cloud obscuring the sun*[1]

IN DIRECT SUNLIGHT

Temperature of—		
Air.	Turgid leaf.	Wilted leaf.
°C.	°C.	°C.
34.2	33.0	37.7
33.0	32.4	37.0
34.2	33.0	39.7
33.0	31.2	35.8
31.8	32.0	35.0
33.8	32.8	37.2
32.9	31.6	35.8
32.1	31.6	34.5
33.5	34.6	37.2
33.0	33.0	37.1
34.0	33.5	37.0
34.0	33.0	38.0
IN DIFFUSE LIGHT, CLOUD OVER SUN		
32.7	31.0	35.7
31.9	29.7	33.5
29.0	28.6	31.2
29.7	28.2	30.2
28.8	28.1	29.7
28.7	27.9	29.5
27.8	27.2	28.7
28.0	27.5	29.0

[1] The observations here tabulated were made between 9.55 and 10.10 a. m.

TABLE X.—*Temperatures of the air and of two leaves of a cowpea plant, one leaf in direct sunlight and the other shaded by the leaves of the plant*

Time	Temperature of—		
	Air.	Shaded leaf.	Leaf in direct rays of sun.
July 24; p. m.	°C.	°C.	°C.
2.00	36.4	32.9	36.1
2.01	35.4	31.9	34.8
2.02	35.4	32.2	34.9
2.03	35.4	31.9	34.9
2.04	35.6	31.8	33.9
2.05	35.5	32.2	35.9
2.06	34.5	31.8	34.4
2.07	36.1	32.9	35.4
2.08	35.4	33.0	35.6
2.09	36.4	32.9	36.4
2.10	35.0	32.4	33.4
2.11	34.4	31.4	34.7
2.12	34.7	31.9	35.4
2.13	34.4	32.4	35.6
2.14	34.9	31.9	34.4
2.15	35.2	32.2	34.4
2.16	36.1	32.8	34.9
2.17	36.6	33.4	35.9
2.18	35.9	32.9	36.0
2.19	34.8	32.6	34.9

Other investigators have observed that the temperature of turgid leaves in diffuse light is lower than in the direct sunlight. Blackman and Matthaei (*2*) found that the internal temperature of the detached leaves of cherry laurel in direct sunshine was from 4° to 13° C. higher than that of the air, but that when the same leaf was placed in the shade its internal temperature was only 1° to 1.5° C. higher than the air that surrounded it. Smith (*14*) found that the internal temperature of leaves in the shade varied from 1.5° C. below to 4° C. above that of the air, but that the internal temperature of the same leaves placed in direct sunshine reached a temperature of as much as 15° C. above that of the surrounding air.

SUMMARY

(1) *Method.*—By means of a thermoelectrical device approximately 10,000 observations were made in a study of the relationships of the temperature of the air to that of attached leaves of corn, sorghum, cowpeas, soybeans, alfalfa, pumpkin, and watermelon growing under field conditions at Manhattan, Kans., during the summer of 1922. The temperature of the leaves of these plants was studied along four lines: The relation of leaf temperature to the rate of transpiration, the temperature of the leaves during the day and night, the temperature of different portions of the leaf, and the temperature of the leaves in direct and in diffuse sunlight.

(2) *Influences to be considered.*—The temperature of a leaf is influenced by the temperature of the air, by the available water supply in the soil, by air currents, by the type of leaf, by the intensity of the light to which it is exposed, and by other factors, so that any data presented in regard to the temperature of leaves must be considered as relative only to the conditions that prevailed when the temperature determinations were made.

(3) *Temperature fluctuations.*—Under ordinary field conditions during the daylight hours, the temperature of the leaves and of the surrounding air is not constant even during so brief a period as a few seconds, but shows sudden and marked fluctuations which vary from a fraction of a degree centigrade to as much as 4° C. or more. Consequently, the average of a number of consecutive determinations gives a more exact index of the temperature behavior of leaves and the surrounding air than a single determination. Each temperature value reported for these experiments is the average of from 10 to 20 separate determinations taken during a 10 to 20 minute period.

(4) *The relation of leaf temperature to the rate of transpiration.*—For a large number of determinations during the hours of 9 a. m. to 4 p. m. the average temperature of the wilted leaves of corn, sorghum, soybeans, and cowpeas was respectively, 1.85°, 1.55°, 2.8°, and 4.65° C. higher than the temperature of the turgid leaves of these plants under the same conditions, with the exception of the amount of water in the soil. During the transpiration-temperature experiments, the percentage of available water in the soil above the wilting coefficient was 2 to 4 per cent for the wilted plants and 10 to 12 per cent for the turgid plants. The average transpiration rate of the turgid leaves was much higher than that of the wilted leaves. The ratio of the rate of transpiration of the turgid leaves to the rate of transpiration of the wilted leaves was as 2.5 to 1 in the case of corn and sorghum, and as 3.5 to 1 in the case of cowpeas and soybeans.

(5) *The temperature of the leaves during the day and night.*—(*a*) During the hours of early morning and evening and when the general climatic conditions are relatively mild, the temperature of the turgid leaves of the plants examined is slightly below the temperature of the surrounding air. The temperature of the leaves during the night is approximately that of the surrounding air, according to the observations made. During the day, however, from 9 a. m. to 4 p. m., under the general climatic conditions prevailing during the growing season in Kansas, different species of plants show a different behavior of the temperature relationship of their turgid leaves and the surrounding air.

(*b*) The temperature of the turgid leaves of corn, sorghum, pumpkin and watermelon in direct sunlight may fluctuate slightly above or below air temperature, but the average temperature of the leaves is approximately that of the surrounding air. In the case of corn, the average of over 1,000 determinations of leaf temperature under a wide range of conditions was 30.64° C., while the average air temperature for an equal number of determinations during that time was 30.58° C. A thousand observations on the temperature of leaves of sorghum and the surrounding air showed an average of 30.64° C. for the former and 30.66° C. for the latter.

(*c*) The average temperature of the turgid leaves of soybeans in 500 observations was 33.66° C., while the average temperature of the air was 33.13° C. The temperature of the leaves of soybeans was thus, under the conditions of this experiment, approximately 0.5° C. higher than that of the air.

(*d*) The average of 500 temperature observations on the leaves of cowpeas was 0.2° C. lower than the average temperature of the surrounding air, while the leaves of alfalfa consistently showed a temperature somewhat less than 1° C. below the temperature of the air.

(6) *Temperature of different portions of the leaf.*—The experiments with the leaves in direct sunlight showed that the temperature of the base of the leaf is always lower than the temperature of the tip region. This temperature difference varies from 1° to 1.5° C., depending upon the nature of the leaf and upon the available water supply.

(7) *Temperature of leaves in direct and in diffuse sunlight.*—The data obtained show that in diffuse sunlight the temperature of attached turgid leaves of the plants studied is always lower than that of the surrounding air. The average difference between the temperature of the leaves and that of the air varied from 0.1° to 3° C., while the maximum difference observed was 5° C. In direct sunlight the temperature of the turgid leaves of most plants fluctuates above and below air temperature, but as soon as a cloud obscures the sun the temperature of the leaf almost immediately drops below the temperature of the air and remains there until the leaf is again exposed to direct sunlight.

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